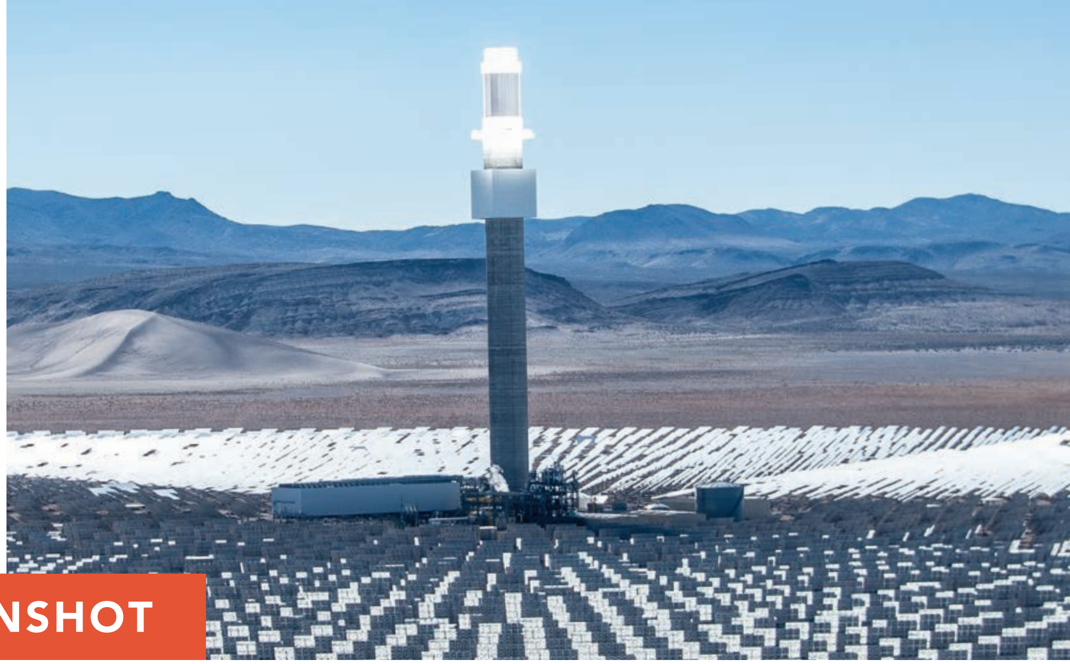
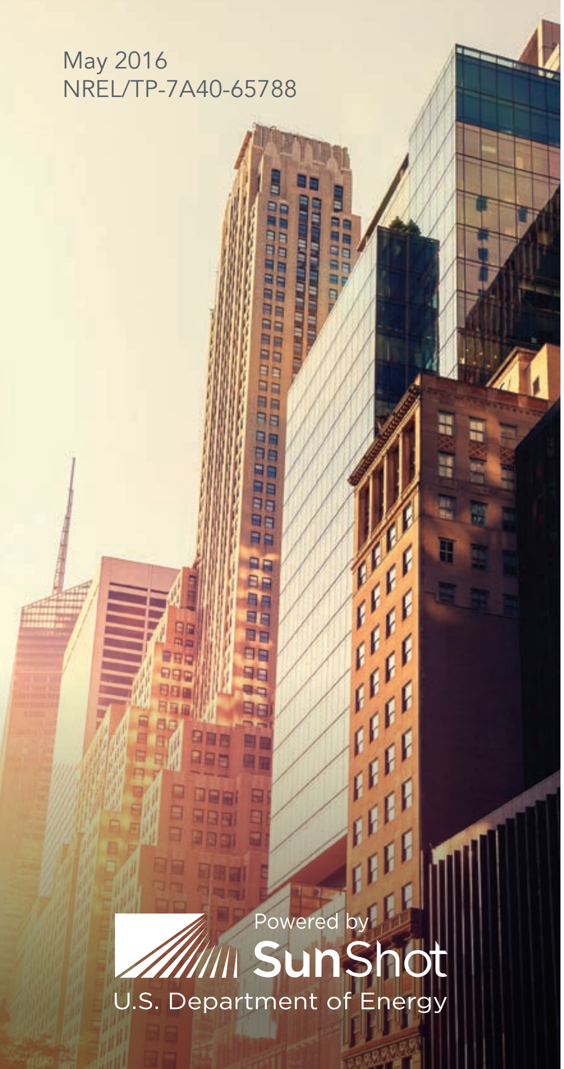


ON THE PATH TO SUNSHOT

Emerging Opportunities and Challenges in U.S. Solar Manufacturing



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On the Path to SunShot: Emerging Opportunities and Challenges in U.S. Solar Manufacturing

Donald Chung, Kelsey Horowitz, and Parthiv Kurup

National Renewable Energy Laboratory

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Preface

The U.S. Department of Energy launched the SunShot Initiative in 2011 with the goal of making solar electricity cost-competitive with conventionally generated electricity by 2020. At the time this meant reducing photovoltaic and concentrating solar power prices by approximately 75%—relative to 2010 costs—across the residential, commercial, and utility-scale sectors. To examine the implications of this ambitious goal, the Department of Energy's Solar Energy Technologies Office (SETO) published the *SunShot Vision Study* in 2012. The study projected that achieving the SunShot price-reduction targets could result in solar meeting roughly 14% of U.S. electricity demand by 2030 and 27% by 2050—while reducing fossil fuel use, cutting emissions of greenhouse gases and other pollutants, creating solar-related jobs, and lowering consumer electricity bills.

The *SunShot Vision Study* also acknowledged, however, that realizing the solar price and deployment targets would face a number of challenges. Both evolutionary and revolutionary technological changes would be required to hit the cost targets, as well as the capacity to manufacture these improved technologies at scale in the U.S. Additionally, operating the U.S. transmission and distribution grids with increasing quantities of solar energy would require advances in grid-integration technologies and techniques. Serious consideration would also have to be given to solar siting, regulation, and water use. Finally, substantial new financial resources and strategies would need to be directed toward solar deployment of this magnitude in a relatively short period of time. Still the study suggested that the resources required to overcome these challenges were well within the capabilities of the public and private sectors. SunShot-level price reductions, the study concluded, could accelerate the evolution toward a cleaner, more cost-effective and more secure U.S. energy system.

That was the assessment in 2012. Today, at the halfway mark to the SunShot Initiative's 2020 target date, it is a good time to take stock: How much progress has been made? What have we learned? What barriers and opportunities must still be addressed to ensure that solar technologies achieve cost parity in 2020 and realize their full potential in the decades beyond?

To answer these questions, SETO launched the *On the Path to SunShot* series in early 2015 in collaboration with the National Renewable Energy Laboratory (NREL) and with contributions from Lawrence Berkeley National Laboratory (LBNL), Sandia National Laboratories (SNL), and Argonne National Laboratory (ANL). The series of technical reports focuses on the areas of grid integration, technology improvements, finance and policy evolution, and environment impacts and benefits. The resulting reports examine key topics that must be addressed to achieve the SunShot Initiative's price-reduction and deployment goals. The *On the Path to SunShot* series includes the following reports:

- Emerging Issues and Challenges with Integrating High Levels of Solar into the Electrical Generation and Transmission Systems (Denholm et al. 2016)
- Emerging Issues and Challenges with Integrating High Levels of Solar into the Distribution System (Palmintier et al. 2016)
- Emerging Opportunities and Challenges in Financing Solar (Feldman and Bolinger 2016)

- Utility Regulatory and Business Model Reforms for Addressing the Financial Impacts of Distributed Solar on Utilities (Barbose et al. 2016)
- The Role of Advancements in Photovoltaic Efficiency, Reliability, and Costs (Woodhouse et al. 2016)
- Advancing Concentrating Solar Power Technology, Performance, and Dispatchability (Mehos et al. 2016)
- Emerging Opportunities and Challenges in U.S. Solar Manufacturing (Chung et al. 2016)
- The Environmental and Public Health Benefits of Achieving High Penetrations of Solar Energy in the United States (Wiser et al. 2016).

Solar technology, solar markets, and the solar industry have changed dramatically over the past five years. Cumulative U.S. solar deployment has increased more than tenfold, while solar's levelized cost of energy (LCOE) has dropped by as much as 65%. New challenges and opportunities have emerged as solar has become much more affordable, and we have learned much as solar technologies have been deployed at increasing scale both in the U.S. and abroad. The reports included in this series, explore the remaining challenges to realizing widely available, cost-competitive solar in the United States. In conjunction with key stakeholders, SETO will use the results from the *On the Path to SunShot* series to aid the development of its solar price reduction and deployment strategies for the second half of the SunShot period and beyond.

Acknowledgments

The authors thank the Solar Energy Technologies Office team for its support of this report and Robert Margolis of NREL for his management and oversight of the *On the Path to SunShot* report series. We also acknowledge and thank the following individuals for their valuable input during the analysis and publication process: Ben Gallagher (GTM Research), Barbara Goodman (NREL), Chuck Kutscher (NREL), Joyce McLaren (NREL), David Mooney (NREL), Robin Newmark (NREL), Gian Porro (NREL), Stephen Shea (Suniva), Mary Werner (NREL), and Mike Woodhouse (NREL). The authors also thank Jarett Zuboy (consultant) and Mike Meshek (NREL) for editorial assistance.

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John Frenzl of NREL designed the covers for the *On the Path to SunShot* report series.

List of Acronyms

Al	aluminum
AR	anti-reflective
ASP	average selling price
BNEF	Bloomberg New Energy Finance
BSF	back surface field
CAFD	8Point3
CAGR	compound annual growth rate
CapDR	capital demanded
CAPEX	capital expenditures
CapIR	capital investment rate
CDB	China Development Bank
CdTe	cadmium telluride
CIGS	copper indium gallium selenide
COGS	cost of goods sold
c-Si	crystalline silicon
CSIQ	Canadian Solar
CSP	concentrating solar power
DNI	direct normal irradiance
DOE	U.S. Department of Energy
EBIT	earnings before interest and tax
EBITDA	earnings before interest, tax, depreciation, and amortization
EPC	engineering, procurement, and construction
EU	European Union
EVA	Economic Value Added or ethylene-vinyl acetate
FIT	feed-in tariff
FSLR	First Solar
GM	gross margin
GW	gigawatt
HCE	heat collecting element
HHI	Herfindahl-Hirschman Index
HTF	heat transfer fluid
IBC	interdigitated back contact
IC	total invested capital
ID	inner diameter
IEA	International Energy Agency
IPH	industrial process heat
IPP	independent power producer
IRR	internal rate of return
ITC	investment tax credit
JASO	JA Solar
JKS	Jinko Solar
JV	joint venture
LCOE	levelized cost of energy
mc	microcrystalline
MIIT	Ministry of Industry and Information Technology

MT	metric ton
MW	megawatt
MWe	megawatt electrical
N	nitrogen
NOPAT	net operating profit after tax
NREL	National Renewable Energy Laboratory
O	oxygen
OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
p.a.	per annum
PERC	Passivated Emitter Rear Contact
PPA	power purchase agreement
PPE	property, plant, and equipment
PV	photovoltaic(s)
Q	quarter
R&D	research and development
ROIC	return on invested capital
ROW	rest of the world
RPS	renewable portfolio standard
SCA	solar collector assembly
SCE	solar collector element
SETO	U.S. Department of Energy, Solar Energy Technologies Office
SGR	sustainable growth rate
Si	silicon
SPWR	SunPower
TB	Tianwei Baobian
TES	thermal energy storage
Ti	titanium
TSL	Trina Solar
USD	U.S. dollar
VIF	variance inflation factor
W	watt
WACC	weighted average cost of capital
YGE	Yingli Green Energy
YoY	year over year
Z or Z-score	Altman Z-Score (Z)

Executive Summary

The U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) has set a goal of hosting solar manufacturing facilities in the United States with an annual capacity equivalent to annual domestic demand (Carr 2015). While not explicitly part of the original *SunShot Vision Study* (DOE 2012), this is nonetheless a target that the SETO is pursuing. However, in both the photovoltaic (PV) and concentrating solar power (CSP) industries, domestic manufacturing capacity has fallen short of domestic demand.

To understand the possible factors leading to this relative lack of domestic capacity, we review a range of academic literature, market reports, financial data, and other information sources to assemble a broad view of the general development of the solar PV and CSP industries. Topics examined include policy, technology development, financial metrics, industry structure, competitive environment, and other drivers that have shaped these industries to date. This report aims to provide insights into the future development of PV and CSP globally while identifying potential opportunities and challenges specific to the U.S. industries through 2020 and beyond.

With respect to the PV industry, we document the following key findings:

- The global PV market has changed dramatically over the past five years. Module prices plummeted, global deployment grew strongly and shifted, and China became a major demand market while consolidating its dominance in PV manufacturing. China's rise in manufacturing came about through a unique, complex, and interdependent set of circumstances. These included policy factors, financial factors, strong global market demand set against capacity shortages, and a resulting free flow of goods, services, and labor that accelerated the transfer of knowledge stocks into China. The rapid and protracted capacity build-out that followed is unlikely to be replicated because many of the key conditions that enabled the strong growth have begun to change.
- PV manufacturing faces challenges globally and in the United States. Over the next five years, the relatively low price of incumbent electricity generating sources in most large global PV markets will limit pricing achievable for PV products and services. This factor, combined with slowing rates of manufacturing cost reductions, may constrain profit opportunities for firms and poses a potential challenge to the sustainable operation and growth of the global PV manufacturing base. In the United States, manufacturers also face a factors-of-production cost disadvantage compared with competing nations—including $0.06/W higher crystalline silicon PV production costs compared with China.
- The United States has general and PV-specific characteristics that provide opportunities to exploit global industry changes and accelerate U.S. manufacturing expansion. Cost reductions for standard PV modules appear to be slowing, and the path to continued reductions will require improved cell and module efficiencies typically found with innovative, advanced device architectures. A greater reliance on innovation could benefit U.S. PV manufacturers. The United States ranks highly in general measures of competitiveness and innovative capacity as well as attractiveness for PV manufacturing, it is a world leader in PV patents and research and development (R&D) expenditures, and U.S. PV manufacturers already are pursuing diverse technological innovations. Finally, global PV demand growth is expected to average 13% annually through 2020, and the

United States could be the second-largest PV market through that year. Diversification of global demand is also expected to turn several U.S. neighbors into substantial markets—potentially giving the Americas 21% of global demand in 2020. If, as expected, PV manufacturers place increasing emphasis on proximity to attractive demand markets, the United States likely will attract manufacturing facilities. However, the competition among countries to attract PV manufacturing will remain intense.

- Solar employment, including both the PV and CSP industries, is expected to reach 220,000 jobs by 2016 but might contract slightly thereafter as the threat of the investment tax credit (ITC) step down in 2017 has caused a large buildup in demand for projects delivered in 2016. However, in the medium- to long-term, solar employment could again surpass 220,000 jobs by 2020 and expand further to 335,000 jobs by 2030 if solar installations reach the SunShot-modeled estimate of 330 GW (302 GW of PV and 28 GW of CSP) of cumulative installed capacity.

With respect to the CSP industry, we document the following key findings:

- After decades of stagnation, U.S. CSP deployment began growing again in the 21st century, while Spain became the world's dominant market for a time. The demand has been met by a CSP supply chain primarily composed of plentiful commodity materials such as steel, aluminum, and glass, which can often be sourced within the domestic market where generating plants are constructed. Although specialty components are required for CSP solar field components—including reflectors, mirror panels, and receiver tubes—these specialty components constitute about 11% of total system installed costs. Only a few companies and countries, including the United States, have developed the capacity to supply such specialty components.
- CSP manufacturing faces challenges globally and in the United States. Particularly compared with PV, CSP systems are much more complex and require a much larger minimum effective scale, resulting in much higher total CAPEX requirements for system construction, lengthier development cycles, and ultimately higher costs of energy produced at this time. These CSP characteristics also favor large, well-funded manufacturers and can potentially bar new disruptive startup companies. In addition, the global lack of consistent CSP project development creates planning, scale-up, and operational challenges for companies that manufacture specialty CSP components. Finally, the lack of a near-term U.S. market is a formidable challenge to domestic CSP manufacturers. Challenging project economics have stalled or spurred the cancellation of many U.S. CSP projects, and declining PV costs have influenced the switch of some large solar projects from CSP to PV. A current lack of strong domestic CSP demand makes an expansion of U.S.-based CSP production unlikely.
- Several opportunities exist for U.S. CSP manufacturing in the global and domestic arenas. CSP deployment is expected to grow in regions like China, Africa, and the Middle East over the next several years. Combining CSP with thermal energy storage (TES) underpins the potential for more rapid CSP growth beyond 2020, when increasing penetration of PV and other variable generation sources will place a greater emphasis and value on dispatchability. One projection suggests the United States could lead the world in 2050 with about 230 GW of cumulative CSP capacity. The United States could also benefit from the same innovation advantages it possesses with regard to PV. Significant

additional innovation, commercialization efforts, and market development are needed for CSP to become competitive with other generating technologies. Further, development of TES and industrial process-heat (IPH) applications could enhance CSP's unique benefits. Established U.S. R&D centers contribute to a strong CSP-specific innovative capacity and knowledge base, which could confer advantage to U.S.-based firms should domestic demand markets recover.

- In addition to the potential 335,000 direct solar jobs by 2030 (including PV and CSP employment), CSP plants may have significant additional effects on several commodity industries. This is because of the commodity-intensive nature of CSP plants, which typically require approximately 190,000 metric tons (MT) of commodity materials for a 100-MW_e plant. Assuming the SunShot modeled estimates of 28 GW of cumulative CSP capacity are reached by 2030, this could result in an additional 33,000 indirect jobs in the relevant commodity sectors.

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1 Introduction

Growth in solar manufacturing is critical to achieving the SunShot cost and deployment targets set by the U.S. Department of Energy (DOE). In addition, expansion of U.S. solar manufacturing would contribute to the global leadership and domestic economic benefits envisioned by the SunShot Initiative.

This report explores opportunities and challenges facing U.S. solar manufacturers through 2020 and beyond in the context of a rapidly changing global industry. We draw upon a range of sources in seeking to clarify the roles of technology, policy, and financial performance in the development of the solar industry, including the following.

- Academic literature, including articles published in peer-reviewed journals as well as publicly available working papers
- Market research and analysis from commercially available reports and databases
- Financial and other data from commercially available databases, company annual reports, and other public company filings
- Publicly available news articles
- Press releases and public company statements.

After identifying the key drivers and trends contributing to the industry's development to date, we suggest how the industry can develop going forward and how this might affect opportunities for U.S.-based firms.

The report is organized as follows. Section 2 focuses on the solar photovoltaic (PV) industry. Section 2.1 analyzes the development of the PV market to date, including demand growth and distribution, module prices, and trends in manufacturing capacity. The section gives considerable attention to the complex and unique factors leading to China's current domination of global PV manufacturing. Section 2.2 discusses the challenges faced by the global PV industry, including intense competition, the low cost of substitute electricity sources, unsustainable growth, and uncertain corporate finances. It also specifically examines U.S. manufacturers' factors-of-production disadvantages. Section 2.3 presents the opportunities for U.S. PV manufacturing emerging because of global trends, including the potential to increase U.S. market share through technological innovation and the attraction of PV manufacturers to projected high-demand countries in North and South America. It also notes the potential for U.S. PV-related employment.

Section 3 focuses on the concentrating solar power (CSP) industry. Section 3.1 analyzes the development of the CSP market to date, including demand growth patterns and the supply chains for CSP's commodity-based and specialty components. Section 3.2 discusses the challenges faced by the global CSP industry, including the large-scale, complex, and capital-intensive nature of CSP projects as well as the inconsistency of annual CSP demand. It also examines the uncertain near-term prospects for growth in U.S. CSP deployment. Section 3.3 presents the opportunities for U.S. CSP manufacturing emerging because of global trends, including the strong potential for long-term growth and the CSP-manufacturing advantages the United States could realize owing to its innovation infrastructure. It also notes the potential for U.S. CSP-related employment.

2 Solar Photovoltaics (PV)

The global PV market has changed dramatically over the past five years. Module prices plummeted, global deployment grew strongly and shifted, and China became a major demand market while consolidating its dominance in PV manufacturing. China's rise in manufacturing came about through a unique, complex, and interdependent set of circumstances. These included policy factors, financial factors, strong global market demand set against capacity shortages, and a resulting free flow of goods, services, and labor that accelerated the transfer of knowledge stocks into China. The rapid and protracted capacity build-out that followed is unlikely to be replicated, because many of the key conditions that enabled the strong growth have begun to change.

Despite this strong recent growth, PV manufacturing faces challenges globally and in the United States. The capital expenditure (CAPEX) required to build manufacturing facilities—in combination with the current low profitability across the hyper-competitive industry—poses challenges to the sustainable operation and growth of global PV manufacturing. Although the intensity of competition should moderate as weaker players are forced out and the industry consolidates, end-market-driven price limits on products and services will continue to constrain profit opportunities for firms. In the United States, manufacturers also face a factors-of-production cost disadvantage compared with competing nations—including $0.06/W higher crystalline silicon (c-Si) PV production costs compared with China.

That said, the United States has general and PV-specific characteristics that provide opportunities to exploit global industry changes and accelerate U.S. manufacturing expansion. Cost reductions for standard PV modules appear to be slowing, and the path to continued reductions will require improved cell and module efficiencies typically found with innovative, advanced device architectures. A greater reliance on innovation could benefit U.S. PV manufacturers. The United States ranks highly in general measures of competitiveness and innovative capacity as well as attractiveness for PV manufacturing (Manyika et al. 2012; Deloitte 2013; World Economic Forum 2014), it is a world leader in PV patents and R&D expenditures (Zheng and Kammen 2014; BNEF Desktop Portal 2015; Earth Policy Institute 2014), and U.S. PV manufacturers already are pursuing diverse technological innovations. Finally, global PV demand growth is expected to average 12% annually through 2020, and the United States could be the second-largest PV market through that year. Diversification of global demand is also expected to turn several U.S. neighbors into substantial markets—potentially giving the Americas 17% of global demand in 2020. If, as expected, PV manufacturers place increasing emphasis on proximity to attractive demand markets, the United States likely may attract manufacturing facilities (BNEF Desktop Portal 2015; James 2015; GTM Research 2015; Grace and Serota 2015; and Labastida and Gauntlett 2015). However, the competition among countries to attract PV manufacturing will remain intense. By 2014, the U.S. solar industry employed over 175,000 workers, with roughly 80% employed in downstream, non-manufacturing activities. As employment is strongly tied to demand and installations, solar jobs are expected to reach 220,000 in 2016 (The Solar Foundation 2016), and could grow to 335,000 by 2030 if SunShot deployment targets are realized (330 GW cumulative installations across both PV and CSP).

The following sections expand on these points.

2.1 PV Market Development to Date

Over the past five years, the global PV market changed dramatically. Module prices plummeted, global deployment grew strongly while becoming redistributed and most notably China became a major demand market and consolidated its dominant global position in PV manufacturing. This section tracks those trends, with a focus on the unique—and likely irreproducible—conditions that led to China's rise.

2.1.1 Lower PV Prices, Strong Global Demand Growth, and Redistribution

The global PV market grew at a 51% compound annual growth rate (CAGR) between 2006 and 2014, although year-over-year growth was extremely volatile (Figure 1). Country-specific demand swung dramatically over this period, with Germany and later Italy dominating the years 2006–2012, only to contract sharply after thereafter. The United States and Japan had more consistent yet still robust growth between 2008–2014, while China grew very quickly after 2010 and became the largest single market by 2013.

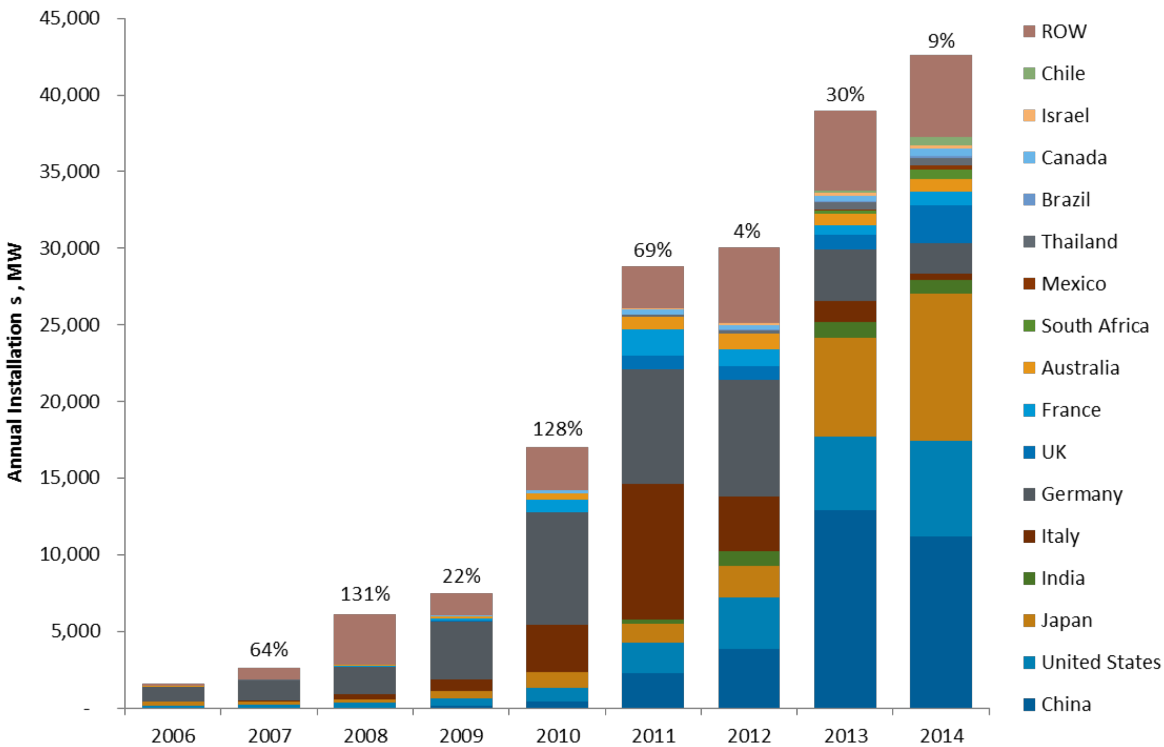

Figure 1. Market development and year-over-year growth, 2006–2014

Data from James 2015, Labastida and Gauntlett 2015, BNEF Desktop Portal 2015, GTM Research 2015, and Grace and Serota 2015

Average module selling prices dropped sharply during 2008–2012, in part fueling the strong downstream demand witnessed over this period. Several factors contributed to PV price reductions (see Section 2.3.1 and Appendix A), but here we examine two key drivers: (1) a steep drop in polysilicon prices due to additional polysilicon capacity and supply coming online, and (2) substantial overcapacity in cell, wafer, and especially module capacity.

CAGRs in manufacturing capacity were strong from the 2000s through 2011. Polysilicon capacity grew at a 43% CAGR between 2009 and 2011 (our data series begins in 2009), while between 2007 and 2011 wafer, cell, and module capacity also grew sharply at CAGRs of 65%, 73%, and 74%, respectively (see Section 2.1.2). Owing to an ongoing supply shortage, spot prices for polysilicon peaked at approximately $475/kg in late 2007, only to fall dramatically from then through 2012 because of significant additional polysilicon supply entering the market. Figure 2 shows annual average polysilicon spot prices through this period along with module average selling prices (ASPs).

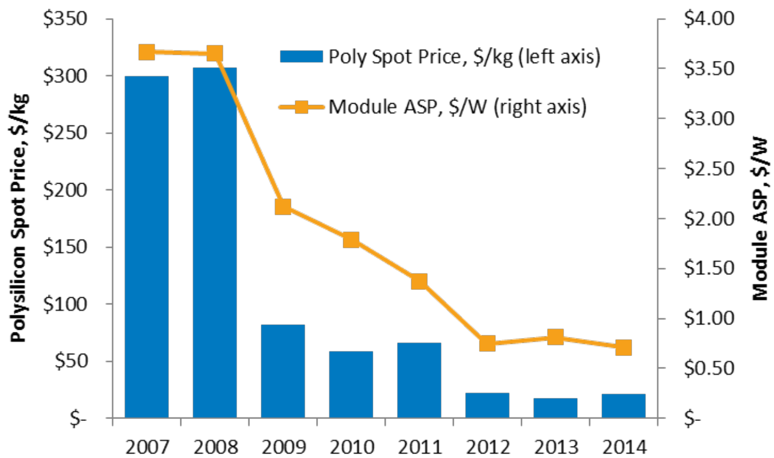

Figure 2. Polysilicon annual average spot prices and global module ASPs

Data from Luo 2011, BNEF Desktop Portal 2015, and Mints 2015

While polysilicon capacity was catching up to demand, the wafer, cell, and module segments had built up significant capacity ahead of polysilicon supply and were already in an overcapacity condition by 2007. The global recession beginning in 2009 slowed demand, which also caused PV inventory to build, just as large amounts of polysilicon capacity were coming online. Figure 3 presents the industry-wide module manufacturing utilization[1] rates between 2007 and 2014 compared to module ASPs. The excess capacity resulting from all these factors persisted until about 2012, after which utilization began to improve steadily and module prices stabilized. Although it is difficult to attribute the precise price-reduction contributions of these and other important factors, supply-demand imbalances clearly played a crucial role in price reductions over this period.

[1] Utilization is total industry production divided by total nameplate capacity. This does not represent the average utilization for any specific plant; rather, it is the average across the entire industry. The percentages may seem particularly low, but this is a function of how we collect capacity information—we collect nameplate capacities, attempt to verify this capacity has been fully built, and do not apply any further qualifications.

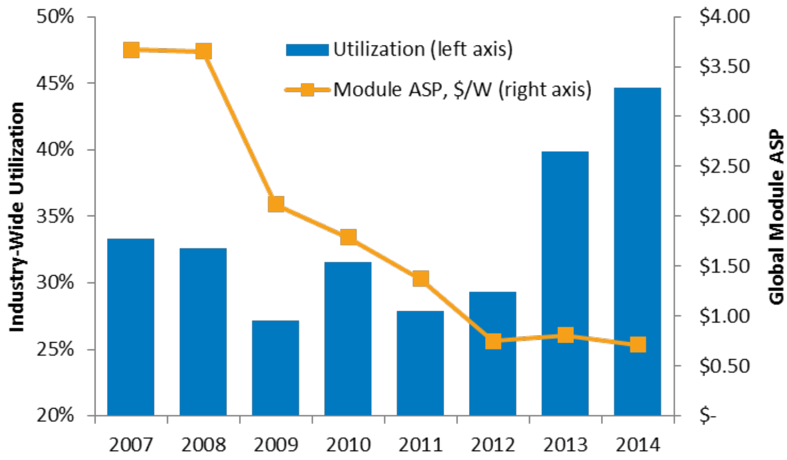

Figure 3. Module manufacturing utilization and global module annual ASPs

Data from ENF 2013, BNEF Desktop Portal 2015, Mints 2015

2.1.2 Chinese Dominance of Global PV Manufacturing Capacity

Because c-Si technologies constitute over 90% of global annual installed capacity (Mints 2015), our review of historical capacity growth focuses on c-Si capacity development. We include all upstream value-chain segments of c-Si PV module manufacturing (as shown in Figure 4): polysilicon, wafer, cell, and module production.

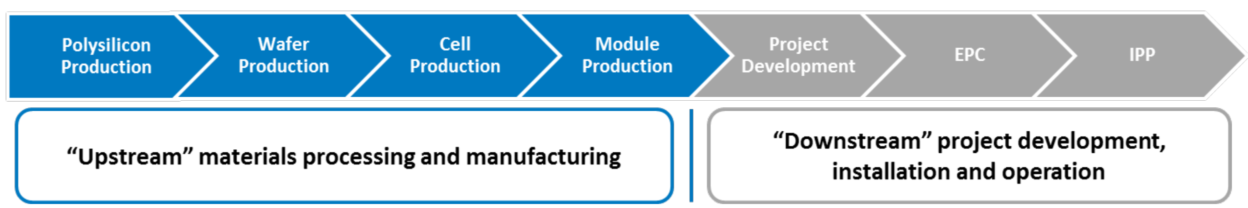

Figure 4. The c-Si PV value chain

EPC = Engineering, Procurement, and Construction—this represents the design and installation of PV systems.

IPP = Independent Power Producer—this represents the ownership and management of PV system assets.

China currently dominates nearly all the upstream value-chain segments for c-Si modules, as shown in Figure 5. Figure 6 through Figure 9 break down the global growth and regional share of each segment. All capacity figures presented in this section represent existing, fully built nameplate capacity only—we do not assess how much of this capacity is effective. These data show trends in regional distribution, share, and growth of total manufacturing capacity.

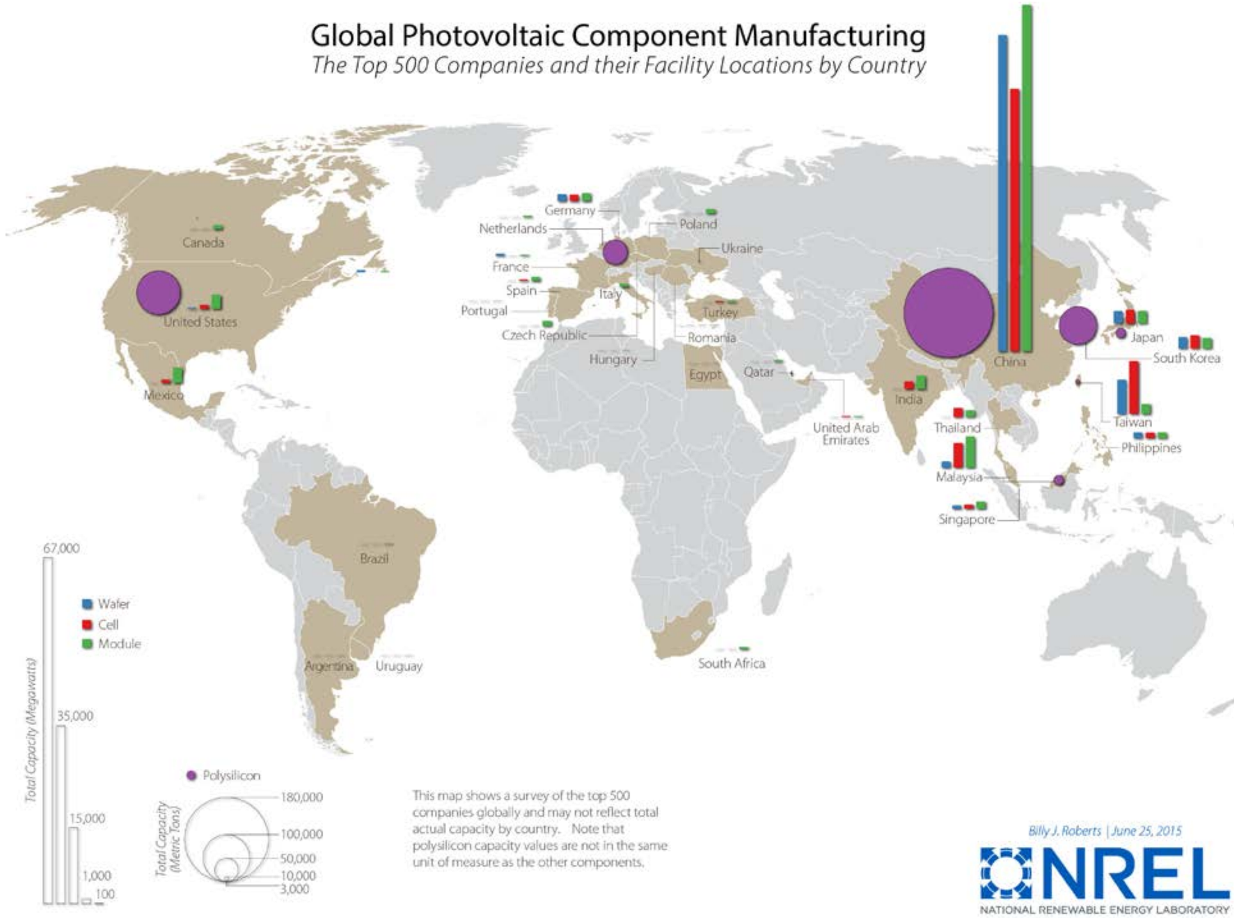

Figure 5. Global distribution of PV manufacturing capacity

Data from ENF 2013, BNEF Desktop Portal 2015, and NREL estimates

Compared to other elements of the value chain, China hosts the lowest share of polysilicon production, with a handful of other countries also hosting significant shares of total global capacity (Figure 6). Still, China is home to 40% of global polysilicon capacity, with the United States, South Korea, and Germany hosting 20%, 17%, and 11%, respectively. The high CAPEX required for new polysilicon capacity—approximately \$0.33/W of annual capacity[2] (Powell et al. 2015) and over \$700 million for a full plant at a competitive scale—can slow incumbents' capacity expansions in reaction to rapidly growing markets. The large initial investment required as well as the complexity of building and operating polysilicon facilities also present high barriers to entry for new competitors. Nonetheless, the shortage in polysilicon capacity that developed in the early 2000s spurred the rapid ramp-up in Chinese polysilicon capacity observed through 2012, though China's share of global capacity has contracted slightly since its peak in 2011.

[2] Estimate for new greenfield facilities built in the United States.

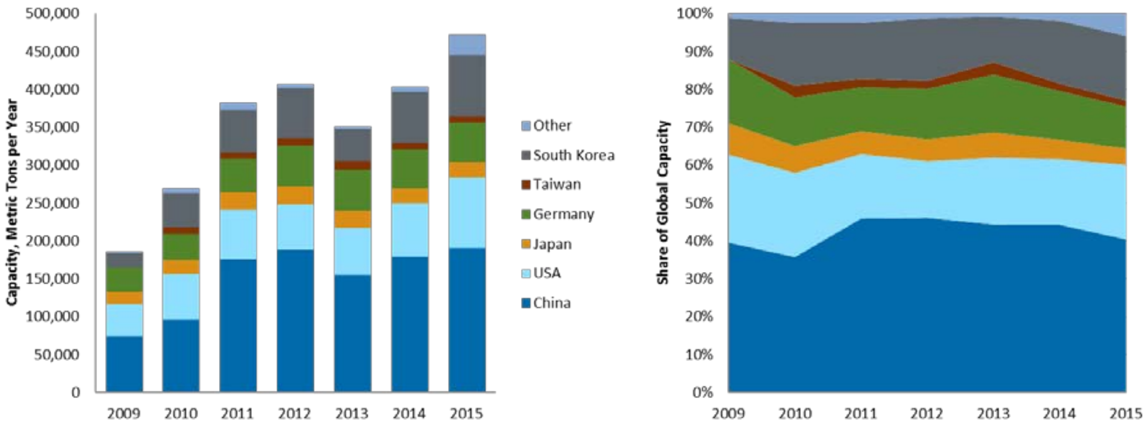

Figure 6. Global polysilicon production capacity and share by region

Data from ENF 2013, BNEF Desktop Portal 2015, and NREL estimates

The wafer, cell, and module elements of the c-Si value chain generally require lower initial investment, and they are relatively simpler to establish and operate competitively. As shown in Figure 7, Figure 8, and Figure 9, China hosts very high proportions of global wafer (80%), cell (65%), and module capacity (67%). However, its share of cell capacity has been waning since 2011, and its share of module capacity has dropped noticeably since 2013. In any case, these figures demonstrate China's rapid scale-up across all segments of the value chain.

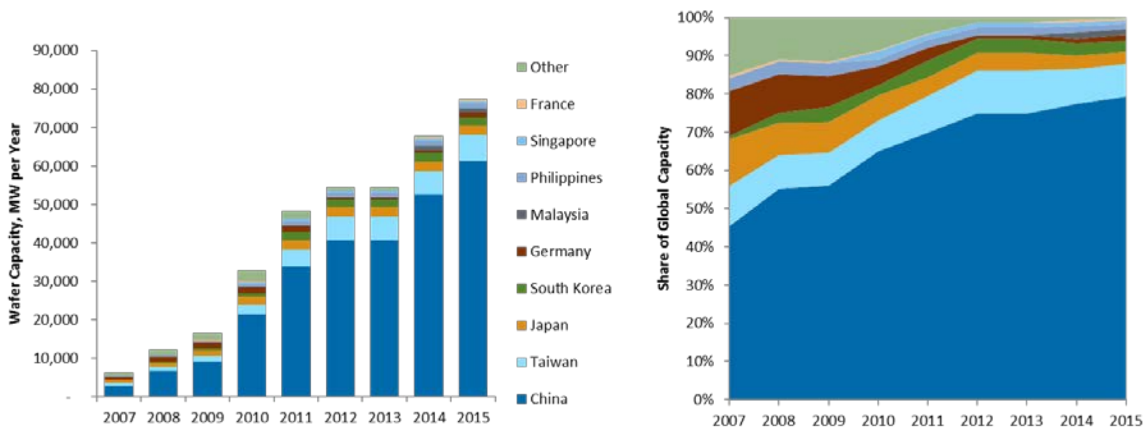

Figure 7. Global wafer production capacity and share by region

Data from ENF 2013, BNEF Desktop Portal 2015, and NREL estimates

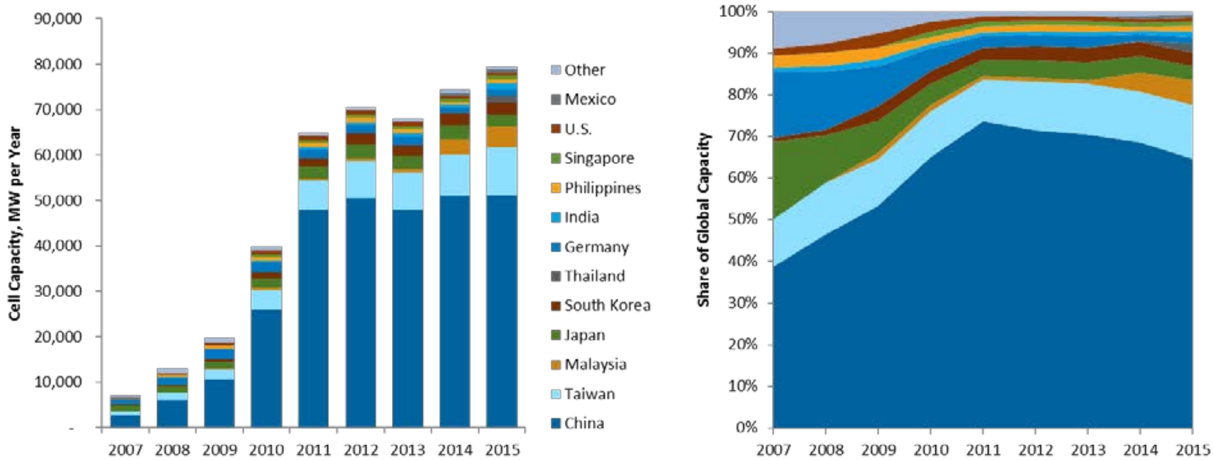

Figure 8. Global cell production capacity and share by region

Data from ENF 2013, BNEF Desktop Portal 2015, and NREL estimates

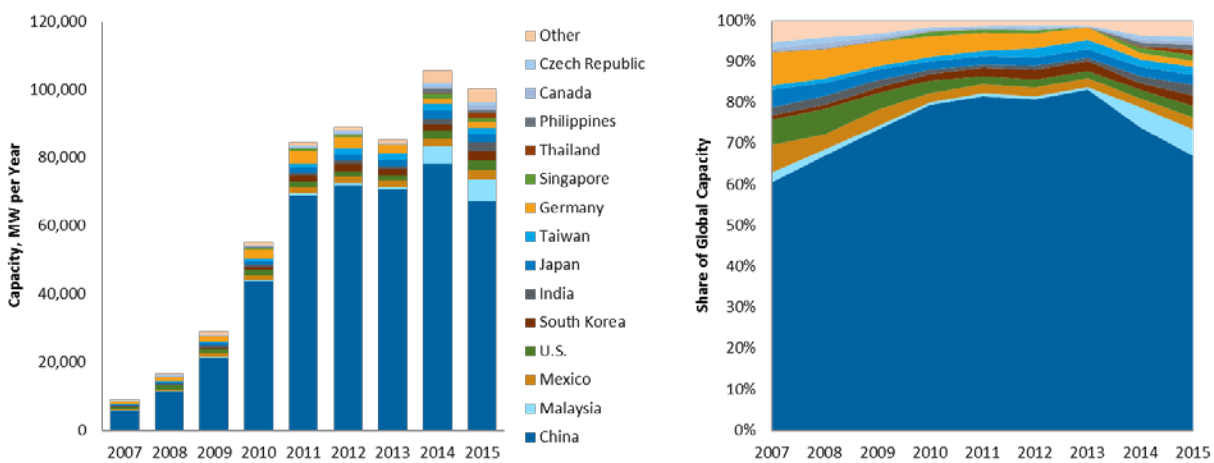

Figure 9. Global module production capacity and share by region

Data from ENF 2013, BNEF Desktop Portal 2015, and NREL estimates

DOE has set a goal of hosting manufacturing facilities in the United States with an annual capacity equivalent to annual domestic demand (Carr 2015). However, U.S. production of wafers, cells, and modules has not kept pace with domestic PV demand (Table 1). Although global growth has been positive across all segments during the period observed, the already-small capacities of wafer and cell manufacturing in the U.S. peaked in 2010–2011 and have generally declined since. Global module manufacturing has grown more strongly from a larger base, but U.S. modules still can meet only a third of domestic demand.

Table 1. U.S. PV Manufacturing Capacity and Demand over Time

	2007	2008	2009	2010	2011	2012	2013	2014	2015E	CAGR
Polysilicon, MT			43,300	59,800	65,029	61,000	61,771	70,050	93,050	14%
Polysilicon, MW			10,070	13,907	15,123	14,186	14,365	16,291	21,640	14%
Wafer, MW	159	267	360	396	536	480	480	430	180	2%
Cell, MW	127	282	656	955	795	795	795	470	700	24%
Module, MW	568	1,043	1,176	1,682	1,651	1,690	1,455	2,055	2,697	21%
U.S. Demand, MW	187	308	468	890	1,916	3,338	4,670	6,226	8,124	60%

A module efficiency of 16% and a polysilicon requirement of 4.3 g/W are assumed to arrive at annual megawatt capacity estimates for polysilicon, which represent 2015 efficiencies and consumption. While this has changed over the period assessed, we apply the current conversion rates across all years because of a lack of annual polysilicon consumption data in wafer manufacturing and because of the intent and context of this table.

Data from ENF (2013), BNEF Desktop Portal (2015), James (2015), GTM Research (2015), Grace and Serota (2015), Labastida and Gauntlett (2015), and NREL estimates

2.1.3 Factors Contributing to Chinese PV Manufacturing Scale-Up

The conditions and mechanisms by which China has dominated production across the c-Si value chain are a unique and complex mix of policy actions, financial conditions, market demand development, technology transfer from other regions and from related industries within China, and local economic development pressures (de la Tour et al. 2010; Grau et al. 2012; Sun et al. 2014; Zhi et al. 2014; Zhao et al. 2014; Quitzow 2015). These factors, and the sequence of their manifestation, resulted in the rapid scale-up of c-Si production in China. This in turn helped China quickly establish itself as the price leader within conventional c-Si technologies because of the importance of scale and learning contributions to PV cost reduction (Nemet 2006; Goodrich et al. 2013; Gan and Li 2015). Our analysis of the combined effect of these key factors suggests that China's recent PV surge likely is not fully replicable today in any location because many conditions have changed.

2.1.3.1 Policy Factors

China treats renewable energy development as a high national priority—renewable energy is one of seven strategic industries the government supports as foundations of future economic growth. Chinese policy at the national level tends to be long term, with a relatively strong centralized structure and multi-year target setting. As in other policy areas, China's renewable energy policy is articulated and coordinated at the highest conceptual level in the Five Year Plan process. More detailed blueprints are given in mid- to long-term plans and targets by the National Energy

Administration and the National Development and Reform Commission as well as in the implementation of the Renewable Energy Law and its periodic amendments.

Chinese federal policy has been split between push (technology and manufacturing development) and pull (demand market development) incentives. From the 1970s to the 1990s, solar pull policies and programs in China focused on renewable energy deployment for rural energy, including remote standalone solar applications. From the 1990s through 2004, a series of policies and programs was implemented to demonstrate small-scale, grid-connected PV applications. Since the passage of the Renewable Energy Law in 2005, policy development has focused on technology scale-up and accelerated deployment for developing domestic and foreign renewable energy markets.

With respect to encouraging manufacturing capacity, provincial and municipal policy (as distinguished from federal policy), as well as explicit and implicit state financial support, have also played equal if not greater roles in developing China's dominant upstream PV sector. Provincial and municipal support commonly includes tax concessions, access to low-cost energy and land, loan interest refunds, and various investment grants (Grau et al. 2012; Deutch and Steinfeld 2015; Quitzow 2015). Financial support mechanisms can be more complex, as detailed in the next subsection.

2.1.3.2 Financial Factors and Access to Capital

Especially critical to the rapid growth of Chinese PV manufacturing has been financial support from municipal governments, investment corporations (with municipal government backing), and commercial and state-owned banks. Government financial support is not always direct. It can include implicit or explicit guarantees structured via semi-governmental intermediary organizations, such as loans provided by development corporations that are in turn guaranteed by municipal governments (Grau et al. 2012). The China Development Bank (CDB) has also provided direct loans and lines of credit to renewable energy companies, including US$47 billion made available between 2010 and 2011. However, these loans and credit facilities were not always well priced and were in fact not heavily drawn against. Instead, the CDB lines of credit effectively served as guarantees, which allowed borrower firms to procure other, presumably more competitively structured facilities from commercial banks. The advantage realized by many Chinese firms in this period of rapid growth was relatively unrestricted access to capital, although not necessarily access to low-cost capital (Provaggi 2013; Bakewell 2015; Quitzow 2015).

Further, many major manufacturers have created complex commercial networks that effectively allow them further state-ensured access to capital. For example, such firms work closely with investors, joint ventures (JVs), and subsidiaries that in turn have direct relationships with the Chinese government. Yingli, Daqo, JA Solar, Trina, Hanwha Q-cells, and Renesola all have financial transactions with major shareholders, JVs, or subsidiaries that have direct relationships with the Chinese government.

While such relatively easy access to capital has helped Chinese firms dominate global PV manufacturing, it has also left many Chinese firms with debt-heavy capital structures. Figure 10 presents average debt-to-capital ratios for 11 Chinese PV firms compared with 7 non-Chinese PV firms—Chinese firms use debt more heavily in their capital structures compared with their non-Chinese counterparts. Whether such debt-heavy capital structures are sustainable in the long term is an open question, especially with respect to potential future capacity expansion and growth. The question of sustainability is explored in Sections 2.2.2 and 2.2.3.

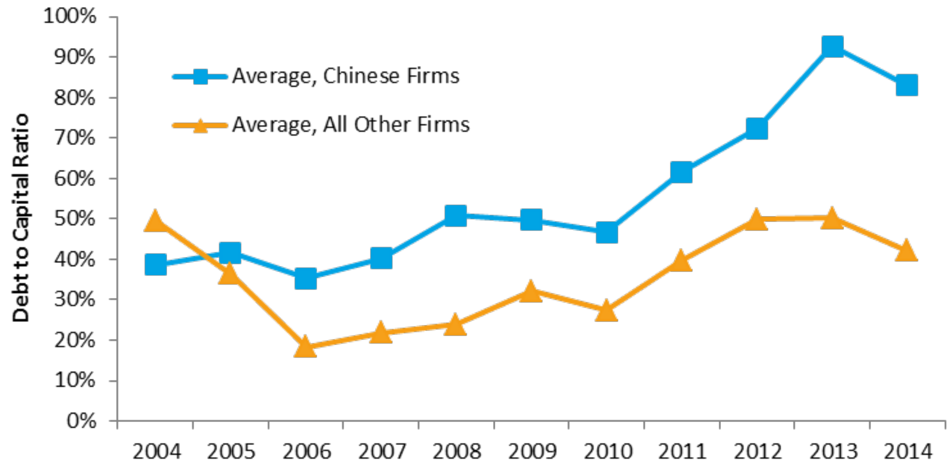

Figure 10. Average total debt-to-capital for Chinese compared with non-Chinese PV firms

Data from Bloomberg L.P. 2015; data includes 11 Chinese PV firms and 7 non-Chinese PV firms

2.1.3.3 Knowledge- and Technology-Transfer Mechanisms

The influx of PV manufacturing technology and knowledge into China from Germany and other regions has been critical to building Chinese manufacturing capacity. PV technology and knowledge began to flow in earnest into China around 2003, primarily through labor mobility and trade in goods and services.

Trade in goods and services manifested primarily in the purchase of foreign capital equipment used in PV manufacturing. German and other PV capital equipment vendors began to sell equipment to nascent Chinese manufacturer customers, allowing them access to state-of-the-art production technology. Further, manufacturing line startup and other production consulting services were sold along with capital equipment. Finally, some equipment vendors offered entire turnkey production lines covering wafer, cell, and module production, effectively easing market entry for new firms and facilitating expansion by less experienced firms (de la Tour et al. 2011; Quitzow 2015).

The influx of solar personnel from abroad was also critical in transferring knowledge quickly into the Chinese PV manufacturing industry. Chinese firms actively recruited employees and managers with training and experience gained from foreign manufacturing firms and organizations. The resulting injection of key know-how contributed to China's rapid scale-up of competitive manufacturing capacity (de la Tour et al. 2011; Quitzow 2015).

2.1.3.4 Global Market Demand Development

Global—and particularly German—market demand also played a critical role in building Chinese manufacturing capacity, which initially focused almost exclusively on production for export markets. Although, in 2000, Germany's 14% share of global demand trailed Japan's 55%, by 2005 the German market grew to 62% of global demand while Japan's share shrank to 20%

(Figure 11). Germany's rapid demand growth, set against shortages of polysilicon and thus PV modules, set into motion a unique period of dynamic international interactions and interdependencies, in particular between Germany and China.

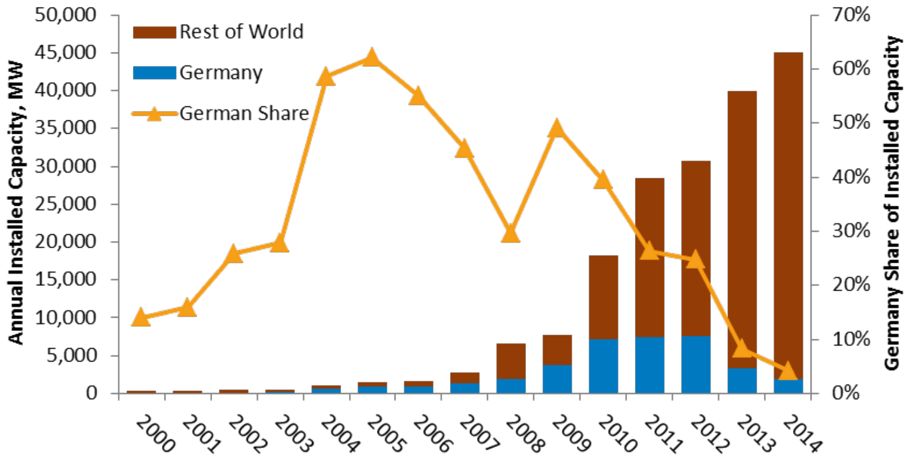

Figure 11. German market development and share of global demand

Data from BNEF Desktop Portal 2015

2.1.3.5 Interplay of All Factors in Scaling Up Chinese PV Manufacturing

Quitzow (2015) details the interplay of policy, finance, technology/knowledge transfer, and demand growth that spurred manufacturing capacity expansion in China. We summarize key points in Table 2. This account of China's emergence as the dominant PV manufacturer highlights the unique circumstances and reinforcing linkages that produced today's market. Other regions attempting to create a competitive PV manufacturing base likely could not replicate all the favorable conditions experienced in China during its critical growth phase.

Even within China, conditions have changed—the federal government has recognized the potentially unsustainable nature of its upstream PV sector and is attempting to rationalize and consolidate the number of competitors. At the end of 2013, the Ministry of Industry and Information Technology (MIIT) created national PV industry manufacturing standards[3] and issued a list of 109 companies (since expanded to 180) that met those standards (Gouras 2014; Wang 2015). While the standards are not particularly difficult to meet, this approach is an attempt to support larger, more sophisticated firms at the expense of less competitive companies not included on the list. Only listed firms are eligible for support from the CDB and for other incentives meant to encourage listed firms to acquire presumably uncompetitive, unlisted firms.

[3] The standards are concerned with capacity, utilization, product performance (e.g., minimum efficiencies), resource consumption, and environmental impact (Gouras 2014; Wang 2015).

Table 2. Key Dynamics and Interactions Contributing to Chinese Manufacturing Capacity Scale-Up

Period	Key Dynamics and Interactions
1990s–2003	• Germany becomes a key global demand market (Figure 11). • While German manufacturing firms rush to supply the market, over 50% of demand still relies on imports. • German capital equipment firms also enter the market, making PV production equipment more readily available. • China establishes a small number of PV manufacturing firms, originally serving China's small domestic demand resulting from the *Brightness Program* and the *National Township Electrification Program.* • Chinese private pioneer firms enter the market, recognize Germany as a key export opportunity, and structure themselves as export-oriented companies. Capital equipment purchases from Germany and other foreign suppliers begin.

2004–2008	• Ongoing German (and global) supply shortage motivates Chinese pioneer firms to ramp up scale and production capacity to fill the demand. A second wave of new Chinese firms also enters the market.
	• Chinese pioneers, as well as the second wave of Chinese firms, rapidly acquire know-how and skills via several mechanisms, most importantly:
	  o Continued purchases of capital equipment, primarily from German firms, often in conjunction with consulting services.
	  o Recruitment of highly skilled personnel, including executives and other personnel trained in foreign businesses and universities.
	  o OEM and other collaborations with German manufacturers and international R&D centers.
	  o Foreign direct investment.
	• Chinese financial support to its growing manufacturing base ramps up via financing from state-owned banks as well as provincial and municipal financial institutions.
	• Chinese provincial and local incentives also become increasingly available (tax breaks, access to low-cost energy and land, loan interest refunds, various investment grants).
	• Chinese firms begin to access global private and public equity markets for additional capital.
	• China also leverages country-internal mass production expertise from related industries, with entrepreneurs acting as knowledge integrators—this creates a unique knowledge base in high-volume, low-cost PV production.
	• International legitimacy of Chinese firms is firmly established owing to German OEM agreements, collaboration, and general market adoption.
	• In 2008, Chinese producers ship 1.1 GW of modules, 20% of global supply (Mints 2015).
	• A lack of polysilicon capacity becomes a critical bottleneck in the PV module supply chain.

Period	Key Dynamics and Interactions
2009–2011	• Global polysilicon capacity catches up to demand—as wafer through module capacity had been built up ahead of polysilicon, oversupply conditions quickly emerge, and module prices begin to drop (Figure 2). • German and other EU FITs do not adjust at the same rate as the module price declines, causing higher demand given very favorable project economics at new lower costs. • Existing international commercial linkages and knowledge transfer and development mechanisms are deepened. • Chinese capital equipment vendors begin to enter the market with lower-priced tools, and a Chinese component supplier base emerges. • Chinese government begins supporting supply-side solar more actively. CDB makes $47 billion in credit facilities available to Chinese solar and wind manufacturers. • Noting potential instability in foreign markets, Chinese government also begins to institute domestic market pull efforts in earnest via the *Renewable Energy Law*, *Golden Sun*, and *Solar Rooftops Programs* plus PV concession tenders. • By 2011, China is a top-five demand market, installing 2.3 GW of systems, or 8% of global demand in that year (data from BNEF Desktop Portal 2015, James 2015, and Labastida and Gauntlet 2015). • By 2011, Chinese wafer through module producers dominate global capacity and production. Chinese module shipments reach 11.6 GW, 46% of global supply (Mints 2015).

2.2 PV Challenges

New capacity across the value chain likely will be needed as the market grows towards 100 GW in 2020 (see projections in Section 2.3.2). However, the CAPEX required to build manufacturing facilities (particularly for polysilicon, wafer, and cell facilities), in combination with the current low profitability across the hyper-competitive industry, poses challenges to the sustainable operation and growth of global PV manufacturing. Although the intensity of competition should moderate as the industry consolidates, end-market-driven price limits on products and services will continue to constrain profit opportunities for firms. In the United States, manufacturers also face a factors-of-production disadvantage compared with competing nations.

2.2.1 Intense Competition, Low Cost Substitute Electricity Sources

Applying Porter's "five forces" framework (Porter 1979) to PV manufacturing shows that significant structural pressures act on the industry to constrain pricing and compress margins. Two factors in particular appear to weigh heavily on the industry as a whole: a large number of competing firms, resulting in a high degree of rivalry, and the low cost substitute electricity-generation sources. These factors together drive the industry to compete largely on the basis of price.[4]

[4] While a certain level of perceived product quality and financial stability—often termed "bankability"—are important to PV product buyers (system developers and financiers), this does not provide any differentiation, or the

All segments of the c-Si value chain have been highly competitive in recent years. A common measure of competitive intensity within an industry is the Herfindahl-Hirschman Index (HHI). HHI is computed by squaring the market share of every firm within an industry and then summing the resulting squared market shares. HHIs below 15% indicate unconcentrated, highly competitive markets (DOJ 2010). Figure 12 shows each value chain segment has remained significantly below the 15% threshold denoting very competitive markets, although some consolidation seems to have occurred in the wafer, cell, and module segments since 2012.

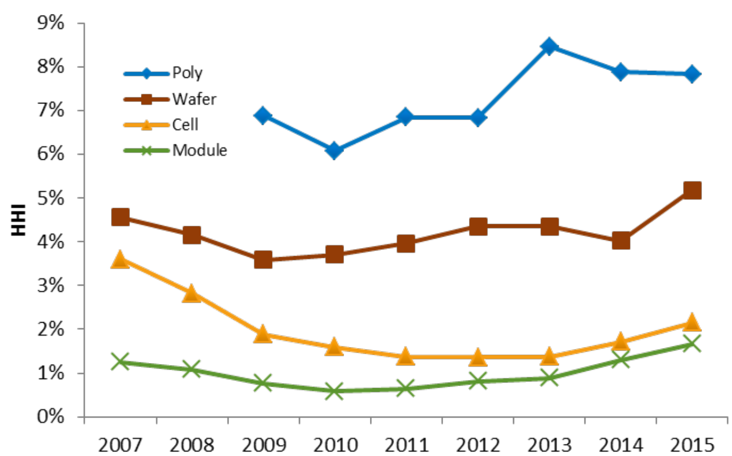

Figure 12. HHI by PV value chain segment

Data from ENF 2013, BNEF Desktop Portal 2015, and NREL estimates

The low cost of substitutes in solar end markets (i.e., electricity markets) also constrains the achievable price for modules and total system installation prices. Fundamentally, energy generated by solar installations must eventually compete with energy rates from incumbent generating sources to gain widespread adoption and market share. Thus, there is an implicit price limit for all products and services within the value chain. Further, major PV markets today are still incentive driven, meaning cost pressures will remain on PV prices at every level—product, installation, operations and maintenance—until the industry can sustainably produce energy at prices competitive with incumbent generation sources without subsidy.

Set against these market forces, PV manufacturers have taken two distinct approaches. The general approach employed by leading c-Si PV manufacturing firms has been to focus on cost reductions while employing relatively standard manufacturing processes and device architectures.[5] The second general approach combines development of differentiated technologies with a focus on downstream activities, such as project development and installation. The U.S. firms SunPower (developer of high-efficiency interdigitated back contact, or IBC, cells) and First Solar (developer of cadmium telluride, or CdTe, modules) adopted this approach

ability to realize a price premium, among leading manufacturing firms. Rather, it is simply the cost of entry to compete.

[5] Modules composed of aluminum back surface field—or Al BSF cells—on both mono- and multicrystalline silicon wafers.

relatively early. While these firms have also by necessity reduced their manufacturing costs over time, they have simultaneously pursued downstream activities to ensure consistent demand for their products and capture additional margins. Figure 13 breaks down each company's share of revenues from upstream versus downstream segments, showing the importance of project-related activities to both firms. Gross margins within each segment are also presented, and we include several leading "standard" c-Si module manufacturers (that produce primarily Al BSF modules through 2014) for comparison purposes.

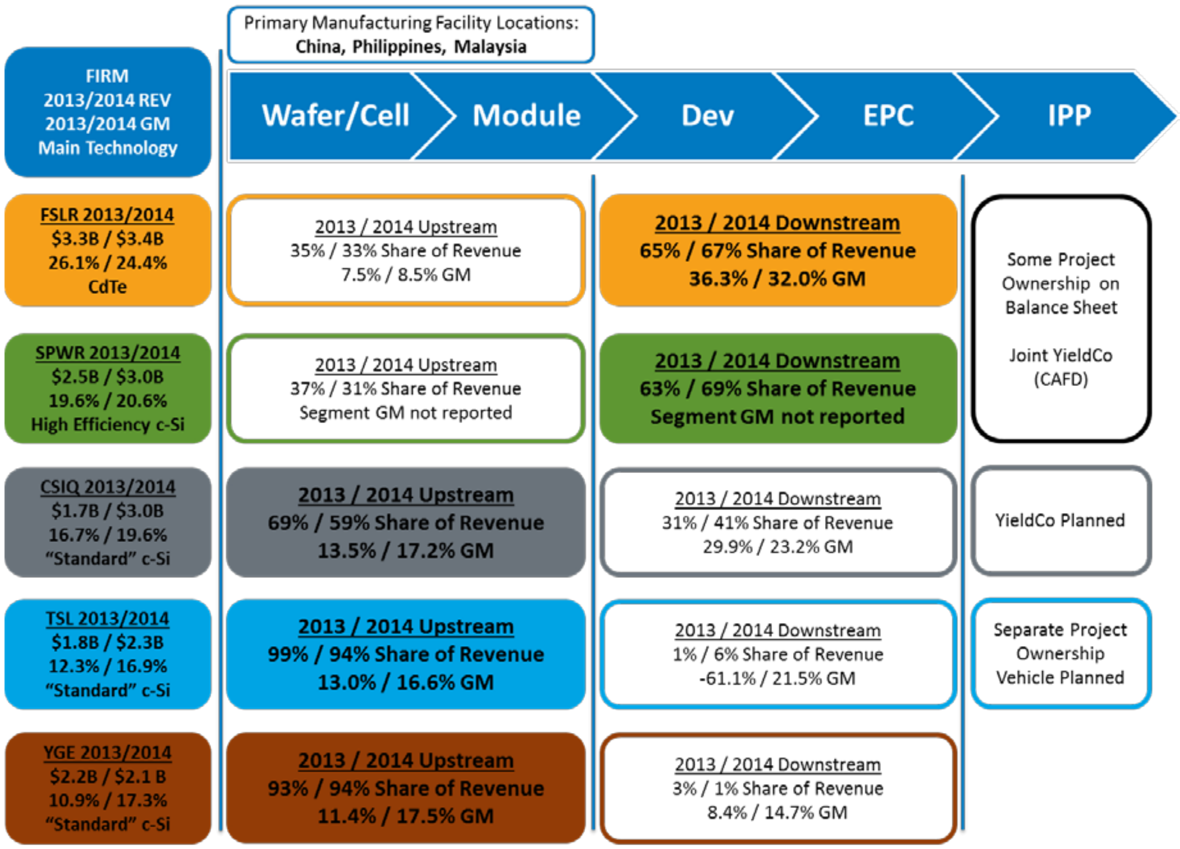

Figure 13. Market approaches of several leading PV firms

CAFD = 8Point3; CSIQ = Canadian Solar; FSLR = First Solar; SPWR = SunPower; TSL = Trina Solar; YGE = Yingli Green Energy; Data from Bloomberg L.P. 2015 and company annual reports; Firms may realize revenues and profits from activities other than those listed, and therefore revenue splits may not sum to 100%.

Data from Bloomberg L.P. 2015 and company annual reports

For most firms examined, 2014 margins are moderately to significantly higher in the downstream segments. By accessing a larger portion of the overall margin available across the total value chain, firms integrated into system development and installation activities can partially offset the impacts of severe price competition in upstream manufacturing segments. Major leading Chinese manufacturers are beginning to build downstream businesses as well. CISQ is relatively advanced on this front, with revenue from project-related businesses growing to 41% of total revenue in 2014.

2.2.2 Potentially Unsustainable Growth

Analysis suggests the global PV industry will struggle to sustain strong growth in the face of high manufacturing CAPEX requirements, low capital investment rates, relatively high leverage ratios, and low profitability. Powell et al. (2015) apply the concept of sustainable growth rate (SGR) to analyze the impact of the CAPEX required for new manufacturing capacity on potential PV industry growth. Table 3 shows the current CAPEX requirements for U.S. PV manufacturing facilities.

Table 3. CAPEX Required for U.S. PV Manufacturing Facilities

	Polysilicon	Wafer	Cell	Module
CAPEX Required per Watt of Annual Production Capacity, $/W/y	$0.33	$0.25	$0.30	$0.13
Average Facility Size in 2015, MW of annual capacity	2,200[6]	1,000	475	240
CAPEX Required for Average Size Facility, millions $	$726	$250	$143	$31

Data from Powell et al. 2015 and NREL estimates

SGR is the maximum growth rate a firm can sustain without changing its existing financial policy with respect to capital structure and dividend payouts, and it is defined as follows:

$$SGR = PRA'T^0,$$

where P = profit/sales (profit margin), R = retained earnings/profit (retention ratio), A' = sales/opening assets (asset turnover), and T^0 = opening assets/opening equity (leverage ratio) (Ashta 2008). SGR assumes these ratios do not change over time.

By modeling the cost and operating characteristics of PV manufacturing facilities using a bottom-up approach, Powell et al. (2015) find that SGR is a strong function of CAPEX—more specifically, of capital intensity, defined as the ratio of property, plant, and equipment (PPE[7]) to revenue—and operating margin. They find the modeled SGR to be well below historic PV industry growth rates, indicating such growth cannot be sustained indefinitely. Further, analysis of the financial performance of several PV manufacturers suggests that internal rates of return (IRRs) on manufacturing capacity investments have generally been below firms' costs of capital, again calling into question the sustainability of industry growth (Powell et al. 2015). Figure 14 presents the average of SGRs for 11 public PV firms (7 Chinese, 4 U.S., and 1 Taiwanese firm) and compares SGRs to year-over-year firm sales and PPE growth over the same period.

[6] Assuming an average polysilicon plant size of 9,500 MT per year and polysilicon consumption of 4.3 g/W.
[7] It is assumed that the PPE balance sheet account for PV manufacturing firms consists primarily of production facilities and equipment and that PPE is a function of manufacturing-related CAPEX. In relation to SGR computation, PPE is considered an asset and thus impacts SGR through A' and T^0.

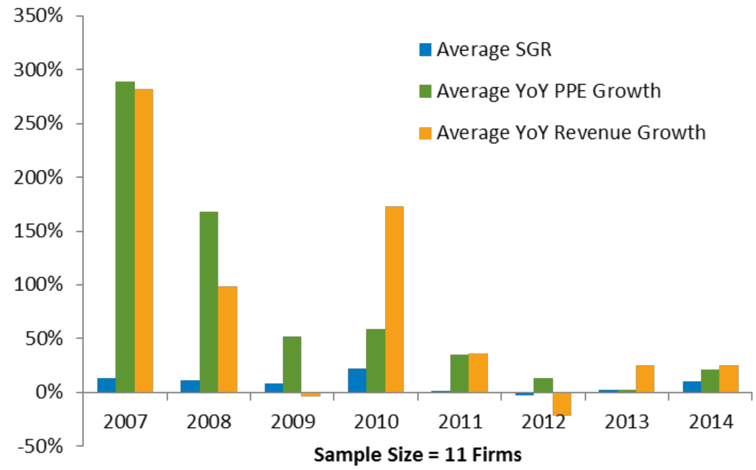

Figure 14. Average SGR vs. year-over-year revenue and PPE growth

Data from Bloomberg L.P. 2015

In nearly all years analyzed, the actual revenue growth rate of firms exceeded their respective SGRs, as did PPE growth. Actual growth over the period 2007–2010 appears to have been driven by positive operating margins (defined as earnings before interest and taxes, or EBIT, divided by revenue) coupled with an increase in leverage, as shown in Figure 15. The impact of poor operating margins and the leveling of debt ratios during 2011–2014 are reflected in lower SGRs, which averaged 3% over the same period.

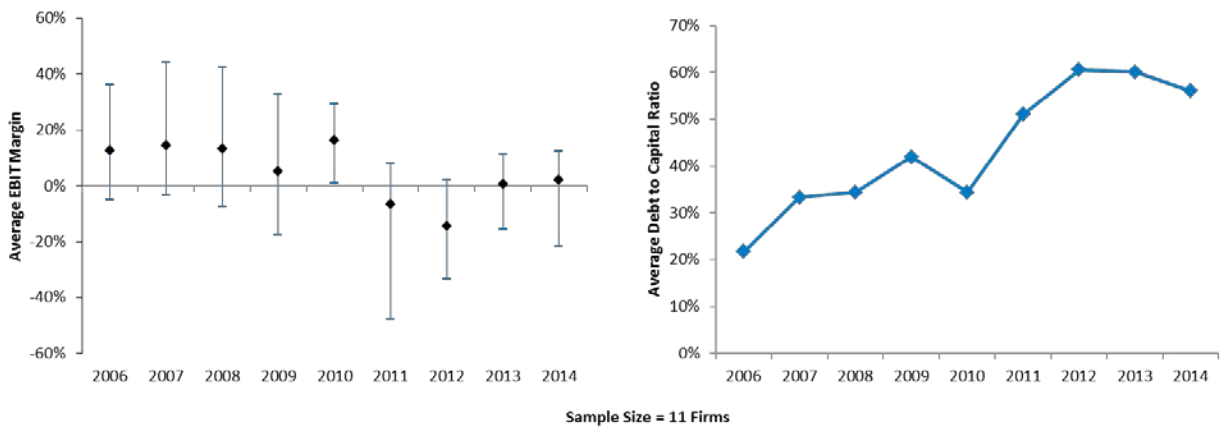

Figure 15. Operating (EBIT) margin average and range (left) and average debt-to-capital ratios (right)

Data from Bloomberg L.P. 2015

Nonetheless, the actual average revenue CAGR was 5% and the average PPE CAGR was 9% between 2011 and 2014. Assuming the ratios constituting SGR do not change going forward, such growth cannot be sustained by definition. If some combination of profitability, CAPEX, and/or leverage ratios is not improved, the long-run growth of the industry could be limited.

Using a different approach, Basore (2015) also finds the growth of the industry may be limited under current market conditions. The question of industry sustainability is explored by modeling the development of total global manufacturing capacity based on comparing manufacturing capital investment rates (CapIRs) to the capital investments needed to build new capacity (capital demand rates, or CapDRs).

CapIR is defined as the amount invested globally in PV manufacturing capacity in a given year divided by the total global manufacturing capacity online in the year prior, and it is assumed to be a function of firm profitability. Figure 16 presents CapIRs for 2006–2014 (slopes of the regression lines represent CapIR: $0.57/W for 2006–2011 and $0.075/W for 2012–2014). The drastic drop in investment rates between 2011 and 2012 is attributable to the heavy capacity buildup leading into 2011 and the resulting extensive overcapacity situation that impacted the industry through 2013.

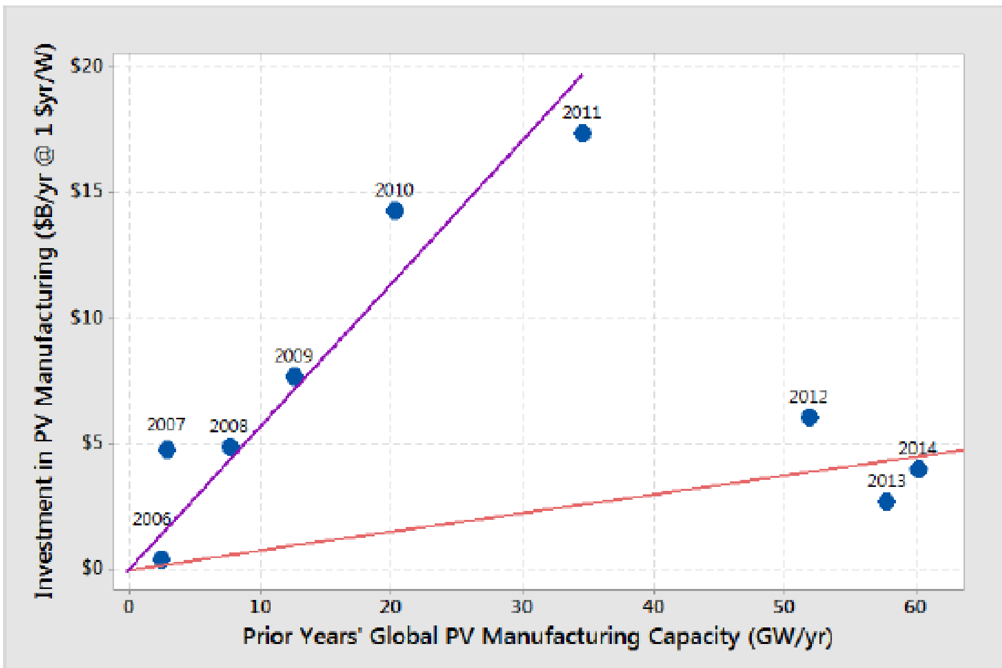

Figure 16. Historical CapIR

Figure from Basore 2015

CapDR is based on the same CAPEX assumption used by Powell et al. (i.e., a total of $1/W of annual capacity, see Table 3) for all upstream segments of the value chain. This number is then converted to an annualized capital requirement by dividing the CAPEX by an assumed 10-year life of manufacturing assets and then adjusting the figure assuming a 10% cost of capital. This results in a CapDR of $0.15/W:

$$\text{CapDR} = \frac{1\,\frac{\$\text{yr}}{\text{W}}}{10\text{ yr}} \text{ x } \left[1 + \frac{10\,\frac{\%}{\text{yr}} \text{ x } 10\text{ yr}}{2}\right] = \$0.15/\text{W}$$

Starting from an assumed global capacity of 64 GW in 2014, CapIR and CapDR are then projected forward on an annual basis and converted to capacity additions in any year, and retirements are netted from the total. In this manner, the total capacity online in any year is determined iteratively. It is also assumed that market demand is not limiting in any case and that 80% of any capacity built will be utilized.

CapIR must be greater than CapDR for manufacturing capacity to grow indefinitely. Under current conditions where CapIR = \$0.075/W and CapDR = \$0.15/W (referred to as the baseline case), CapIR is less than CapDR, and thus capacity will peak in coming years and then contract as depicted in Figure 17 (top). Minor improvements in CapDR or CapIR in isolation have little effect on the modeled peak capacity achieved. If instead CapIR and CapDR are improved simultaneously, pathways to sustained growth are possible as shown in Figure 17 (bottom).

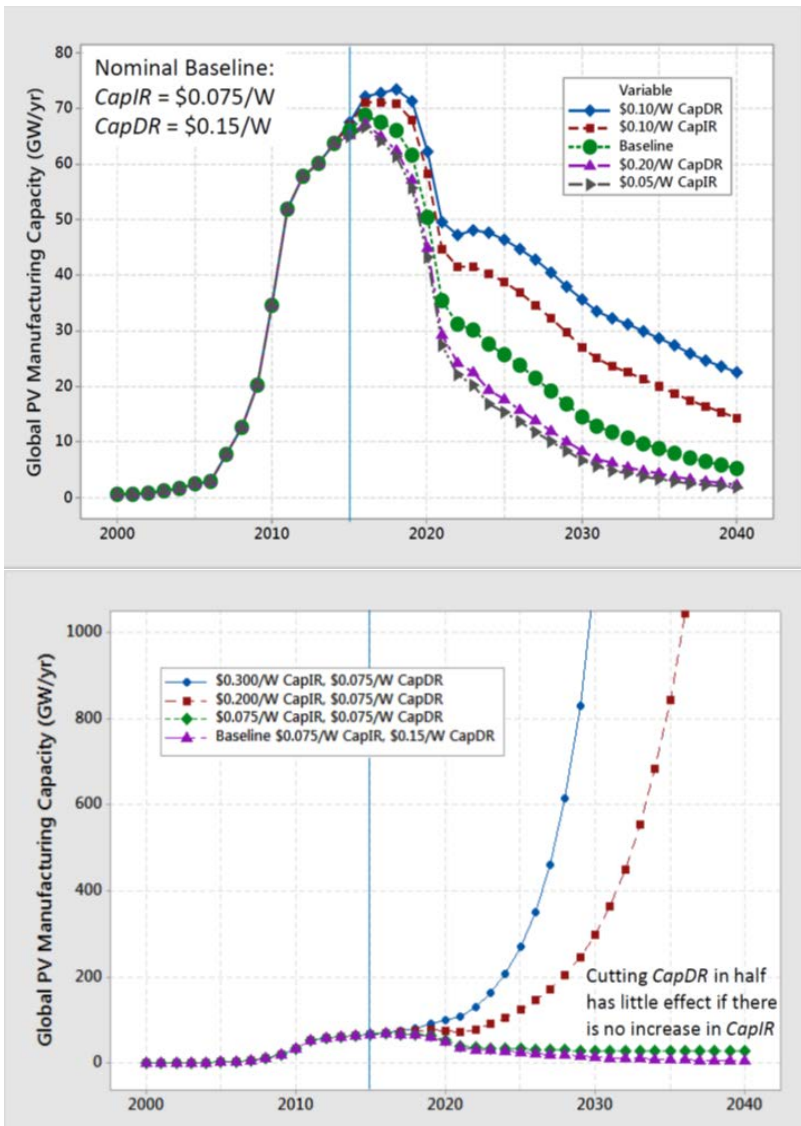

Figure 17. Capacity development under various CapIR and CapDR assumptions

Figure from Basore 2015

2.2.3 Uncertain Corporate Finances

Both of the above analyses show that sustainable PV industry growth at forecasted demand rates (with global demand expected to reach 100 GW by 2020, a 12% CAGR between 2015 and 2020) may be jeopardized under current conditions of firm profitability, reinvestment rates in new manufacturing capacity, and costs of new capacity. Our analysis using two additional, more generalized metrics of financial sustainability and performance—Economic Value Added (EVA™)[8] and the Altman Z-score (Z or Z-score)—casts further questions regarding the health of global PV manufacturers and thus on the industry's ability to sustain growth.

Capacity share data from 2011–2014 suggest the industry is consolidating slightly (Figure 12) and margins are recovering (Figure 15). However, industry-wide financial performance is still struggling, and returns are generally below investor expectations. The latter concept can be quantified by EVA, which measures the value created by a firm. EVA posits that a firm can generate profits and a positive return, but that value is not actually created unless the return generated exceeds the firm's weighted average cost of capital (WACC). EVA is typically defined as follows:

$$\text{EVA} = \text{NOPAT} - (\text{WACC} \times \text{IC}),$$

where NOPAT = net operating profit after tax and IC = total invested capital (Ilic 2010). Recognizing that

$$\text{NOPAT} = \text{ROIC} \times \text{IC},$$

where ROIC = return on invested capital, the EVA equation can be rewritten as follows:

$$\text{EVA} = (\text{ROIC} \times \text{IC}) - (\text{WACC} \times \text{IC}), \text{ and finally}$$

$$\text{EVA} = (\text{ROIC} - \text{WACC}) \times \text{IC}.$$

In this formulation, the concept of EVA is more explicitly interpreted as the return to invested capital in excess of a firm's WACC (the excess return, or ROIC – WACC), scaled by the amount of capital invested. A zero or positive EVA indicates a firm is generating returns at or above its investors' expectations, while a negative EVA implies a firm is not generating returns meeting its investors' expectations. In the case of sustained negative EVAs, a firm's ability to raise capital going forward may be impaired, presenting a possible constraint to growth.

An analysis of EVAs for global public PV firms (Figure 18) reveals that, on average, EVAs have been negative since 2009 (left), and most firms have never generated returns at or above their cost of capital (right). In theory, this calls into question the ongoing ability of the PV industry to raise capital from external sources, which, in combination with the potential limits to self-financed growth (as measured by SGR), suggests a threat to long-term industry growth.

[8] Economic Value Added and EVA™ are trademarks of Stern Stewart & Company.

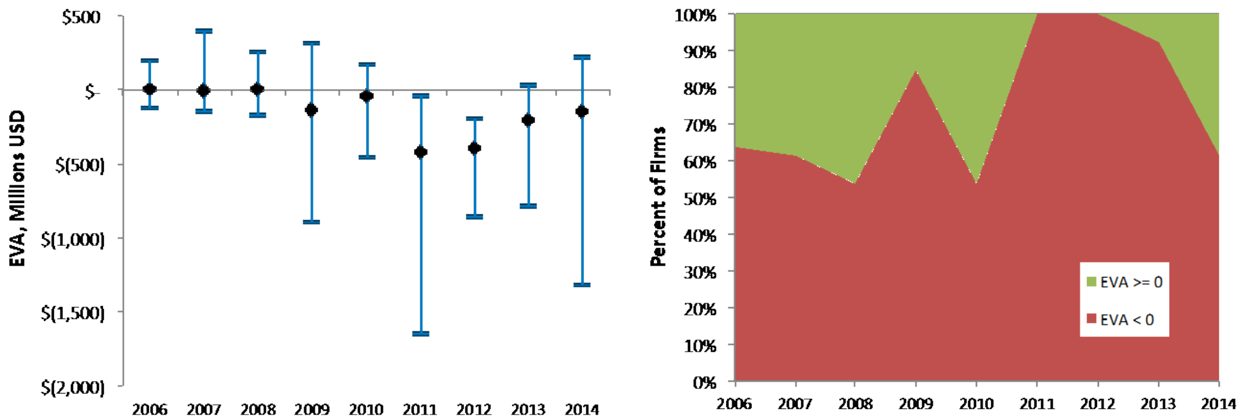

Figure 18. Average and range of EVAs (left) and share of firms with zero or positive EVA (13 public PV companies)

Data from Bloomberg L.P. 2015

Finally, we examine the existential threat posed to firms by current market conditions. The Altman Z-score (Z) is a commonly used metric to assess bankruptcy risk and is computed as follows:

$$Z = 1.2X_1 + 1.4X_2 + 3.3X_3 + 0.6X_4 + 0.999X_5,$$

where X_1 = working capital/total assets, X_2 = retained earnings/total assets, X_3 = EBIT/total assets, X_4 = market value of equity/book value of total debt, and X_5 = sales/total assets. The resulting Z-score is used to classify firms into three broad categories: those that appear safe from bankruptcy ($Z > 2.99$), those in a "gray area" ($2.99 > Z > 1.81$), and those that are distressed and at risk of bankruptcy ($Z < 1.81$) (Altman 1968).

We apply this metric to a number of public PV firms and analyze Z-score development over time. The resulting Figure 19 shows a dramatic shift of firms into the distressed state between 2010 and 2015. This is perhaps unsurprising given the dynamic nature of the industry over this period, specifically the high demand growth requiring significant investment and resources to maintain market share (51% demand CAGR from 2006–2014, Figure 1), considerable buildup of fixed assets (Figure 6 through Figure 9), strong module price erosion (Figure 3), and resulting profitability impacts (Figure 15, at left). While theory suggests that a more concentrated market with fewer, larger competitors should result in less price-based competition—and thus firms exiting the industry may benefit survivors—this may not entirely be the case for the PV industry. Regardless of industry concentration, firms must still compete with incumbent electricity-generation sources, which effectively caps pricing along the value chain.[9] The impact of these price caps on the health and sustainability of firms will depend on the total economics of PV systems, which in turn depend heavily on regional market characteristics and dynamics.

[9] All current major PV markets are subsidy driven, thus price limits are also a function of subsidies available, and price pressure is expected to remain given that most subsidy programs are designed to ramp down over time.

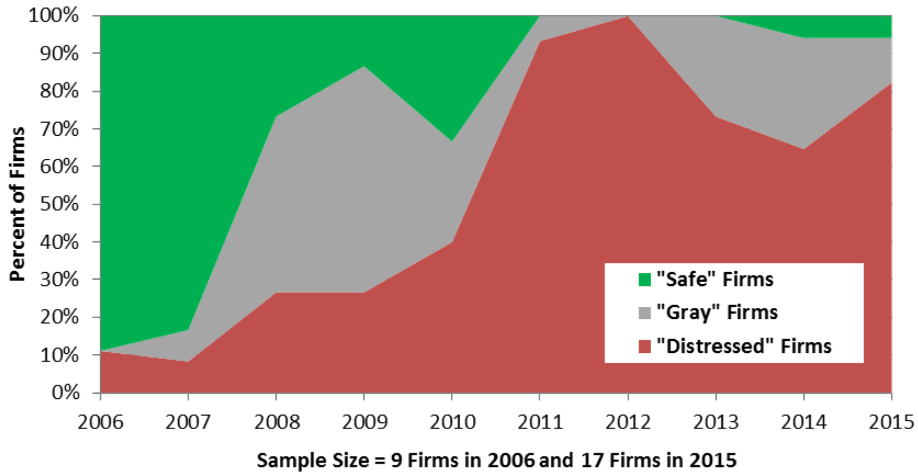

Figure 19. Altman Z-score distribution for public PV firms

Data from Bloomberg L.P. 2015

Finally, continued cost and price reductions are expected through 2020. The sustainability of anticipated price reductions in relation to improved cost structures remains an open question. We examine a simple scenario to provide insight into the dynamics of these basic factors. We begin with the SunShot target for utility-scale PV systems, which is a $0.06/kWh unsubsidized levelized cost of energy (LCOE) for U.S. regions of average insolation (DOE 2012). This target LCOE can be achieved at a system installed cost of $1.10/W. A recent study (Jones-Albertus et al. submitted 2015) finds that one possible path to this SunShot goal requires a module price of $0.40/W in 2020 (and 20% efficiency). Compared to an estimated $0.33/W integrated in-house production cost in 2020 (Wang 2014), this would yield a gross profit of $0.07/W for vertically integrated firms. The 2014 operating expense for four profitable leading manufacturers averaged $0.08/W,[10] suggesting that this combination of projected price and cost would not be profitable. While operating expense per watt for these same manufacturers has improved rapidly in recent years (20% between 2013 and 2014), it is unclear whether this rate of year-on-year reduction can be maintained.

2.2.4 U.S. Factors-of-Production Disadvantage

In addition to the industry-wide challenges discussed above, the United States faces a cost disadvantage in terms of some factors of production compared with certain competing nations. We use bottom-up cost modeling to compare U.S. and Chinese integrated polysilicon through module manufacturing costs for 255-W modules at 15.6% efficiency (multicrystalline silicon modules using p-type 180 µm wafers and Al BSF cells). Table 4 presents the resulting differences in factors of production.

[10] CISQ, Jinko Solar (JKS), JA Solar (JASO), and Trina Solar (TSL). Operating expense per watt is estimated by subtracting EBIT from gross profit and subsequently dividing by each firm's respective annual module shipments. Data is gathered from public company filings.

The total net difference across the value chain is $0.06/W, or about 12% of the modeled Chinese cost of goods sold (COGS). If U.S. material costs were leveled with those observed in China,[11] the net difference narrows to $0.04/W, or 7%. While these differences appear small, if a module selling price of $0.60/W is assumed, this $0.04/W difference ($0.52/W vs. $0.48/W COGS) manifests as a 13% gross margin for U.S. production compared with a 20% gross margin for Chinese production. For context, the industry average gross margin across 13 public PV firms in 2014 was 12.6% (data from Bloomberg L.P. 2015).

Table 4. Comparison of Modeled U.S. and Chinese Vertically Integrated Production Costs

Cost Element	USA, $/W	China, $/W	Difference, $/W
Metallurgical-grade silicon	$0.02	$0.01	-$0.01
Other materials	$0.30	$0.28	-$0.02
Electricity	$0.03	$0.06	$0.03
Direct labor	$0.07	$0.01	-$0.05
Maintenance	$0.03	$0.03	$0.00
Depreciation	$0.09	$0.08	-$0.01
COGS	$0.54	$0.48	-$0.06

Data from NREL analysis

2.3 U.S. PV Opportunities

Opportunities may arise for expansion of U.S. PV manufacturing given the factors discussed in previous sections. Capacity development to date has focused on China, but the unique conditions that led to capacity buildup in that country are shifting. Specifically:

- Ready access to debt and other forms of government support is being focused on fewer competitors, with an explicit aim to consolidate the industry.
- The industry is recovering from a protracted period of price and margin pressure, but continued downward price pressure should be expected until PV can compete with incumbent energy technologies without subsidy. This ongoing price pressure may compromise the ability of firms to sustain growth over the long run based on the current conditions of production cost and investment required for new capacity.
- Cost reductions to date have derived largely from polysilicon supply corrections, increasing scale, and incremental innovation from learning-by-doing. The rate of cost reductions is slowing (IEA 2014a; Wang 2014), and continued improvements will require a greater focus on innovation aiming to: markedly improve efficiencies and system yields; discover radically different processes reducing manufacturing costs; and/or to reduce CAPEX required to build new capacity.

[11] Presumably through increased scale, although some co-location and horizontal integration effects in China may also contribute to the input materials pricing differential.

- PV module and system demand is diversifying, with 14 markets of 1 GW or larger expected by 2020 (BNEF Desktop Portal 2015 James 2015; GTM Research 2015; Grace and Serota 2015; and Labastida and Gauntlett 2015), and manufacturers are placing greater emphasis on locating manufacturing in regions with strong markets.

The United States has general and PV-industry-specific characteristics that may enable it to exploit these industry shifts and accelerate U.S. manufacturing expansion. Innovative capacity and knowledge stock as well as proximity to attractive markets rank highly among factors influencing manufacturing location decisions across industries (Manyika et al. 2012; Deloitte 2013; World Economic Forum 2014). A PV-specific study also shows PV manufacturers weight these factors as highly as traditional production considerations (Anand 2015). Table 5 summarizes the high-level drivers on which these studies are based (with innovation and local market factors in boldface).

Table 5. Summary of High-Level Drivers for Various Competitiveness and Manufacturing Indices

Global Competitiveness Report 2014–2015	2013 Global Manufacturing Competitiveness Index	Global PV Manufacturing Attractiveness Index 2015
• Legal and administrative institutions • Physical infrastructure • Macroeconomic environment • Healthcare and primary education systems • Higher education and training • Goods market efficiency • Labor market efficiency • Financial market development • Technological readiness • **Market size** • Business sophistication • **Innovation**	• **Talent-driven innovation** • Economic, trade, financial, and tax system • Cost and availability of labor and materials • Supplier network • Legal and regulatory systems • Physical infrastructure • Energy cost and policies • **Local market attractiveness** • Health system • Government investments in manufacturing and innovation	• Business environment • **Local and regional market demand** • PV manufacturing support • All-in costs

Data from Manyika et al. 2012, Deloitte 2013, and World Economic Forum 2014

The United States ranks third, third, and fifth respectively in the Global Competitiveness Report 2014-2015, the 2013 Global Manufacturing Competitiveness Index, and the Global PV Manufacturing Attractiveness Index 2015. Rankings of the United States and competing nations, and a summary of the global distribution of PV manufacturing capacity are presented in Table 7.

Opportunities for U.S. manufacturing in the global PV industry may thus turn on two premises. First, cost reductions for standard Al BSF modules appear to be slowing, and the path to continued cost reductions will require improved cell and module efficiencies typically found with innovative, advanced device architectures. While this may play to certain U.S. strengths, it should be noted that competing countries also possess PV technology innovation capabilities.

Second, the United States is projected to be the second-largest PV market through 2020, and it is near several additional markets that are projected to be sizeable.

2.3.1 Market-Share Gains via Cost-Reduction Innovations

Manufacturers in the United States could benefit from a trend toward greater reliance on innovation. Price remains the dominant basis of PV competition, and PV manufacturers will remain focused on cost reductions as governments continue cutting incentives in their drive toward an unsubsidized PV future. However, cost reductions in standard module processing not related to efficiency are slowing (IEA 2014a; Wang 2014). Although Chinese firms sustained annual average module cost reductions of 12% from 2012–2014,[12] year-over-year reductions declined from 16% from 2012–2013 to 8% from 2013–2014 (Jones 2015). BNEF estimates an annual 2.3% cost reduction will be realized by leading producers from 2014 to 2020, with manufacturing costs reaching $0.33/W in 2020 for leading vertically integrated producers (Wang 2014). As incremental improvements to entrenched technologies yield diminished cost reductions, more dramatic innovations in new technologies, designs, processes, and module-efficiency provide opportunities to gain competitive advantage.

Module efficiency is one among many factors that influence PV module prices, including—for c-Si modules—silicon use (driven by wafer thickness), polysilicon price, cumulative production, R&D spending (government and corporate), module manufacturing capacity per company, average plant size, silver prices, other module costs, company margins, the level of industry competition, and supply-demand dynamics. As the relationships between these inputs can be complex, with various feedback mechanisms and time lags, quantifying the impact of individual factors on module price is difficult. Our statistical analysis, however, suggests the following factors had the greatest impact on module price over the past 10 years: manufacturing plant size, other (undefined) factors (which likely included some of the market dynamics discussed here), module efficiency, and polysilicon price, in that order. See Appendix A for details of our analysis and an expanded discussion of factors that affect module costs and prices.

Clearly module innovations that boost efficiency have potential to reduce module and balance of system prices and increase manufacturing competitiveness. For example, if the absolute production costs (not the cost per watt) are held steady for the module modeled in Table 4 (U.S. scenario), increasing the efficiency by 17% (relative) results in a roughly 15% improvement in cost—that is, a 300-W, 18.3%-efficient module would yield a production cost of $0.46/W. The impacts of efficiency at a system level are also profound. Fu et al. find that increasing module efficiency from 16% to 20% (and assuming a constant module price per watt) can reduce system costs from $1.82/W to approximately $1.70/W (Fu et al. 2015). Jones-Albertus et al. (submitted 2015) find that, to reach the SunShot LCOE target of $0.06/kWh (for utility-scale systems at average irradiance conditions in the United States), a 16%-efficient module would need to be priced at $0.20/W, whereas a 20%-efficient module can be priced at $0.40/W—a 100% premium[13]—and still achieve the goal due to the impact of efficiency on reducing BOS costs.

In the real world, manufacturers appear to be investing in greater efficiency as well. Capacity for passivated emitter rear contact (PERC) cell designs (a higher efficiency design compared to

[12] Notably, a period of relatively stable polysilicon prices, suggesting reductions were driven by factors other than polysilicon price.

[13] Contributing to a total installed system price of approximately $1.10/W. This assumes U.S. installation without incentives and roughly average U.S. insolation. These and all other key assumptions are included in the study.

standard Al BSF cells) has expanded from 2.5 GW in 2014 to an expected 7.0 GW[14] in 2015 (Lin 2015), and market share projections for this and other high-efficiency cell technologies support this trend. In contrast, the share of standard BSF cells is expected to contract from nearly 90% of the market in 2014 to approximately 30%–45% in the 2020 timeframe (SEMI 2015).

In this context, the United States could play a larger future role in PV technology development and manufacturing owing to its general innovative capacity and consistent development of PV-specific knowledge stock. The United States has regularly ranked highly in general indices of global competitive strength and innovative capacity as well as manufacturing competitiveness: recently it ranked third in the Global Competitiveness Index (World Economic Forum 2014) and third in Deloitte's Global Manufacturing Competitiveness Index (Deloitte 2013). In addition, a recent GTM report finds the United States among the top five nations in terms of attractiveness for PV manufacturing (Anand 2015).

The United States also ranks highly in simpler measures of innovative capacity: patent counts and R&D expenditures. It accounted for 31% of patent cooperation treaty PV patent applications during 2000–2011 (Figure 20). Its R&D expenditures (corporate plus government) were consistent during 2006–2014, approximately even with Japan's since 2011, and slightly above Germany's since 2009 (Figure 21, at left). China's R&D expenditures have grown steadily since about 2010, and they constituted the largest global share by 2014. However, when R&D expenditures are normalized by each country's module shipments, the United States surpassed Germany and Japan in recent years, while China spent the least (Figure 21, at right).

Finally, U.S.-based PV production tends to be technologically differentiated. First Solar develops CdTe thin film technologies, while SunPower and Suniva develop high-efficiency silicon-based concepts. Solarworld is expanding its U.S. cell capacity with passivated emitter rear contact (PERC) lines, new entrants Silevo and Mission Solar are developing high-efficiency silicon concepts, and Stion is pursuing CIGS thin films. This suggests that U.S. firms already leverage U.S. strengths in innovation to create differentiated high-efficiency (silicon) and high-yield (thin film) products as pathways to lower per-watt costs and/or improved system LCOEs. If the rate of cost reduction continues to slow for traditional BSF modules, the importance of developing more advanced, high-efficiency, and high-yield devices will grow, potentially conferring greater competitive prospects to firms (and nations) that excel at cultivating such innovations. However, it should be noted that key competing nations also possess innovative capabilities and knowledge stock in both PV device design and manufacturing, and so a resurgence in U.S.-based manufacturing based solely on these factors is far from guaranteed.

[14] With 11% of this capacity in the United States and European Union, i.e., outside low-cost producer nations.

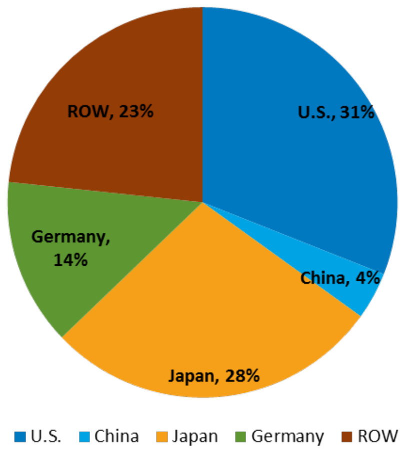

Figure 20. Share of total global PV patent applications, 2000–2011

Data from Zheng and Kammen 2014

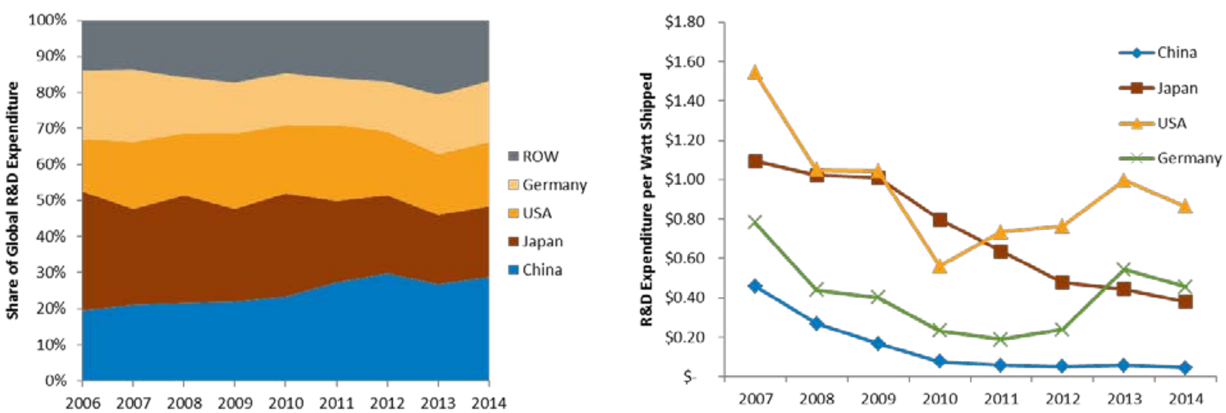

Figure 21. Share of global R&D expenditure (left) and R&D expenditure per watt of modules shipped (right)

Data from BNEF Desktop Portal 2015 and Earth Policy Institute 2014

2.3.2 Attractiveness of North and South American Demand to PV Manufacturers

The United States should remain a major PV market through 2020, and several of its neighbors in the Americas are expected to become significant markets. Thus U.S. PV manufacturing likely will benefit from the weight given to local market attractiveness and access to regional demand in manufacturing location decisions, although this may vary by value chain segment.

The global demand forecast for 2015 through 2020 is presented in Figure 22. The global demand CAGR between 2015 and 2020 is expected to be 13%, compared to a CAGR of 42% between 2010 and 2014. Markets are expected to become less concentrated, with a greater share of total demand coming from a larger number of countries. Still, China, the United States, and Japan are expected to remain the three largest markets, with India and the United Kingdom emerging as the next two largest markets in terms of total expected demand between 2015 and 2020. Historical and expected demand development in these top five markets is shown in Figure 23. Currently, all major markets are subsidy driven, with three of the top five markets employing various feed-in tariffs (FITs) extensively. Key characteristics of the expected top five markets through 2020 are summarized in Table 6 and then described.

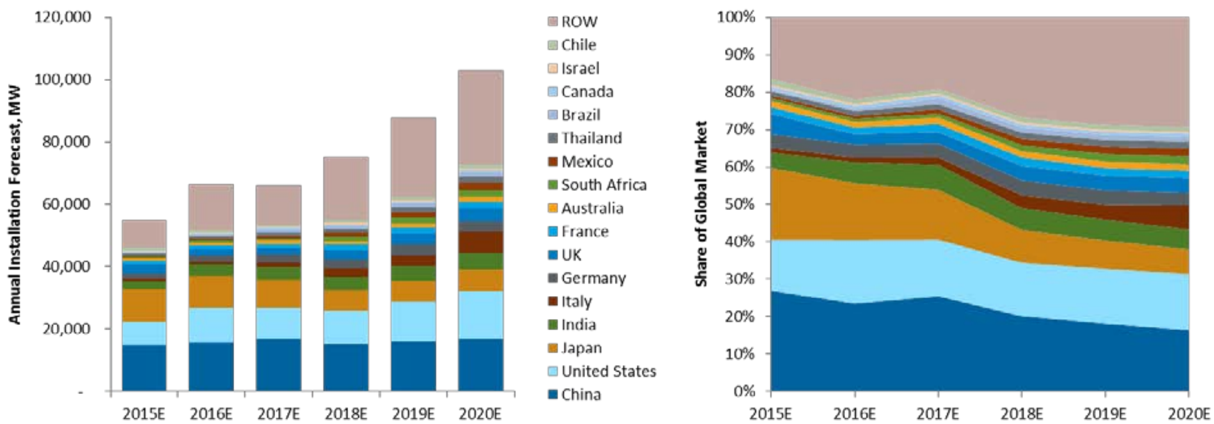

Figure 22. Global demand forecast and regional share

Data from BNEF Desktop Portal 2015, James 2015, GTM Research 2015, and Grace and Serota 2015

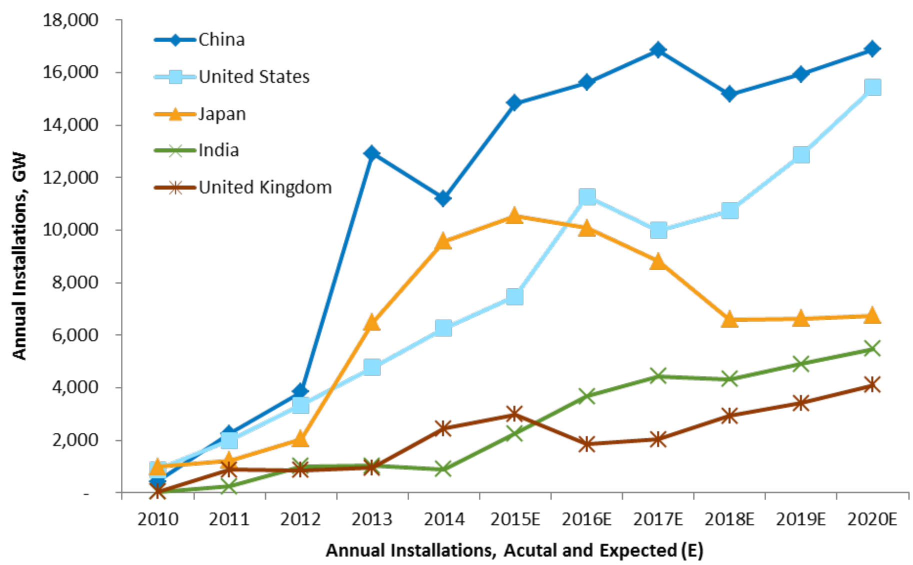

Figure 23. Historical and expected (E) installations, top five markets

Data from BNEF Desktop Portal 2015, James 2015, GTM Research 2015, Grace and Serota 2015, and Labastida and Gauntlett 2015

Table 6. Market Characteristics, Expected Top Five Markets, 2015–2020

Country	Expected New Installations, 2015–2020 (GW)	Expected CAGR, 2015–2020	Approximate Grid Rates	Primary Available Incentives and Drivers	Regional Module ASP at Q4 2014[15]
China	95.3	2.6%	• Residential: $0.07–$0.10/kWh • Commercial: $0.15/kWh • Industrial: $0.11–$0.14/kWh • Agricultural: $0.10/kWh	• $0.15–$0.16/kWh for 20 y, utility FIT • Self-consumption + $0.07/kWh FIT for excess • Annual targets and Five Year Plans	$0.57/W
U.S.	49.8	6.0%	(Continental U.S.) • Residential: $0.09–$0.19/kWh • Commercial: $0.08–$0.18/kWh • Industrial: $0.08–$0.14/kWh	• Tax incentives • State Renewable Portfolio Standards (RPS) • Various other state and local measures • Net metering	$0.72/W
Japan	49.4	-8.5%	• Residential and Commercial: $0.13–$0.24/kWh	• >10 kW: $0.22/kWh for 20 y FIT • <10 kW: $0.27–$0.29/kWh for 10 y FIT • Tax incentives	$0.67/W
India	25.1	19.3%	• Residential: $0.06–$0.10/kWh • Commercial: $0.08–$0.15/kWh • Industrial: $0.07–$0.12/kWh • Wholesale: $0.07/kWh	• Reverse auctions (National Solar Mission) • Various state incentives, including FITs ranging from $0.12–$0.19/kWh • Net metering	$0.58/W
U.K.	17.3	6.6%	• Residential: $0.14–$0.20/kWh • Commercial: $0.15–$0.21/kWh • Industrial: $0.14–$0.16/kWh • Wholesale: $0.05–$0.06/kWh	• 20 y FIT with variable rates by system size: • <4 kW: $0.09–$0.19/kWh • 4–10 kW: $0.09–$0.17/kWh • 10–50 kW: $0.09–$0.17/kWh • 50–100 kW: $0.09–$0.14/kWh • 100–150 kW: $0.09–$0.14/kWh • 150–250 kW: $0.09–$0.14/kWh • >250 kW: $0.09/kWh	$0.65/W

Data from BNEF Desktop Portal 2015, James 2015, Labastida and Gauntlett 2015, and EIA 2015

China. The Chinese market grew at a 133% CAGR between 2010 and 2014, becoming the largest single market globally with annual installations of 11.2 GW in 2014. While China is expected to remain the largest single market through 2020, growth is expected to slow to a 2.6% CAGR between 2015 and 2020, reaching 16.9 GW of annual installations in 2020 (data from BNEF Desktop Portal 2015, James 2015, Labastida and Gauntlett 2015). China's market is primarily FIT-driven, and regular reductions to FIT levels are expected through 2020.

[15] Average selling price from leading Chinese producers (Jones 2015).

Polysilicon pricing in China is affected by duties placed on the import of U.S. and European polysilicon.

United States. The U.S. market grew at a 68% CAGR between 2010 and 2014, reaching 6.3 GW per year in 2014. The market is expected to grow at a 16% CAGR through 2020, reaching 15.4 GW in that year (data from BNEF Desktop Portal 2015, James 2015, GTM Research 2015, Grace and Serota 2015, and Labastida and Gauntlett 2015). The U.S. market is driven by a combination of federal tax credits and a mix of additional state/regional incentives and net metering. The forecast drop in demand between 2016 and 2017 is attributable to the previously expected reduction of the ITC at the end of 2016. While the 30% ITC was extended through 2019 in December 2015, much of the demand that was pulled forward to 2016 because of the anticipated step down may still be realized in 2016, resulting in a spike in 2016 installations with a slight drop in 2017. Steady year-on-year growth from 2017 through 2020 is then expected. Module pricing in the United States is affected by antidumping and countervailing duties placed on cell and module products originating from China (Honeyman et al. 2015).

Japan. The Japanese market grew at an 82% CAGR between 2010 and 2014, reaching 9.6 GW per year in 2014. The market is expected to contract at a -8.5% CAGR between 2015 and 2020, shrinking to 6.8 GW annually owing to limits on solar interconnections as well as political pressure on the cost of subsidizing solar installations (data from BNEF Desktop Portal 2015, James 2015, and Labastida and Gauntlett 2015). However, Japan is expected to remain a major market, even in low-demand scenarios. The market is FIT driven, but regular reductions to tariffs going forward are likely. Further, restarting Japan's nuclear reactors may put downward pressure on retail rates and thus negatively affect solar system economics. However, to date the restart of the nuclear fleet has been slow, with only seven of 42 operable reactors planned to restart operation (Hamada and Sheldrick 2015).

India. The Indian market grew at a 105% CAGR between 2010 and 2014, reaching 900 MW per year in 2014. The market is expected to grow at a 19.3% CAGR between 2015 and 2020, reaching 5.5 GW in 2020 (data from BNEF Desktop Portal 2015, James 2015, and Labastida and Gauntlett 2015). The market is driven by federal policy (National Solar Mission auctions) and effective state policies. Net metering is also expected to play an increasingly important role.

United Kingdom. Between 2010 and 2014, the U.K. market grew at a 222.7% CAGR, reaching 2.4 GW per year in 2014. The market is expected to grow to 4.1 GW by 2020, representing a 6.6% CAGR between 2015 and 2020 (data from BNEF Desktop Portal 2015, James 2015, and Labastida and Gauntlett 2015). The United Kingdom is a FIT-driven market, though other less effective incentive mechanisms also exist. FIT reductions are regularly scheduled in an attempt to bring stability and consistency to the market.

In addition, the number of substantial markets outside these core markets is expected to increase. While only five national markets were larger than 1 GW in 2014, fully 14 are expected to exceed 1 GW in 2020. In addition to the five markets discussed above, these include Italy, Germany, France, South Africa, Australia, Thailand, Mexico, Brazil, and Chile (BNEF Desktop Portal 2015; James 2015; GTM Research 2015; Grace and Serota 2015; and Labastida and Gauntlett 2015).

Manufacturing capacity may be inadequate to meet the 100-GW demand by 2020, requiring new facilities be built and creating opportunities for countries to increase market share. Through September 2015, GTM counts 6.6 GW of new module capacity announcements, all outside of China, including 590 MW planned for the United States (Anand 2015).

Given the importance of local market attractiveness and access to regional demand in manufacturing location decisions, the United States is reasonably well positioned. It is expected to remain a major market through 2020. In addition, Canada, Mexico, Chile, and Brazil are together expected to reach 5.7 GW of demand in 2020, bringing the Americas total to 16.5 GW or 17% of total global demand in that year (data from BNEF Desktop Portal 2015, James 2015, GTM Research 2015, Grace and Serota 2015, and Labastida and Gauntlett 2015).

Although this discussion highlights opportunities for the United States to increase its share of PV manufacturing, key competing countries—many of which also consistently rank highly in studies of national competitiveness (Table 7)—have opportunities as well. It remains to be seen if the increased importance of factors like innovation and market proximity will shift the manufacturing landscape meaningfully.

Table 7. Summary of Manufacturing and Competitiveness Indices

	Global Competitiveness Report Rank	Global Manufacturing Competitiveness Rank	Global PV Manufacturing Attractiveness Index Rank	Nameplate Capacities, 2014			
				Poly, MT	Wafer, MW	Cell, MW	Module, MW
China	14	1	1	190,750	61,360	51,291	67,260
Singapore	2	9	2	-	640	770	1,400
Taiwan	14	6	3	8,000	6,620	10,260	1,920
Malaysia	20	13	4	20,000	1,150	4,750	6,428
United States	3	3	5	93,050	2,380	700	2,757
India	71	4	6	-	-	1,435	2,577
South Korea	26	5	9	80,500	2,200	2,550	2,610
Germany	5	2	10	52,000	1,280	1,206	1,540
Switzerland	1	22	29	-	-	-	-
Finland	4		39	-	-	-	-

Data from World Economic Forum 2014, Deloitte 2013, Anand 2015, and NREL estimates

2.3.3 U.S. Solar Job Estimates

We estimate the future solar employment using actual direct employment data from the National Solar Jobs Census 2015 (The Solar Foundation 2016). This data combines both CSP and PV employment data, and includes a count of direct workers only. While these figures do not represent full time equivalents (FTEs), it is noted that over 90% of workers counted spend 100% of their time on solar-related work.

Historical solar employment data is normalized to either: (1) annual U.S. installed capacity for all non-manufacturing jobs; or (2) to annual U.S. manufacturing capacity[16] for manufacturing jobs to arrive at actual labor intensity (jobs/watt) over time. As labor intensity should be expected to decrease over time through learning effects, the intensities are then plotted against: (1) cumulative installed capacity for non-manufacturing jobs; and (2) manufacturing capacity from the U.S. to develop learning curves. Finally, the curves are used in combination with annual demand and manufacturing capacity projections going forward to arrive at the estimated employment numbers presented in Figure 24.

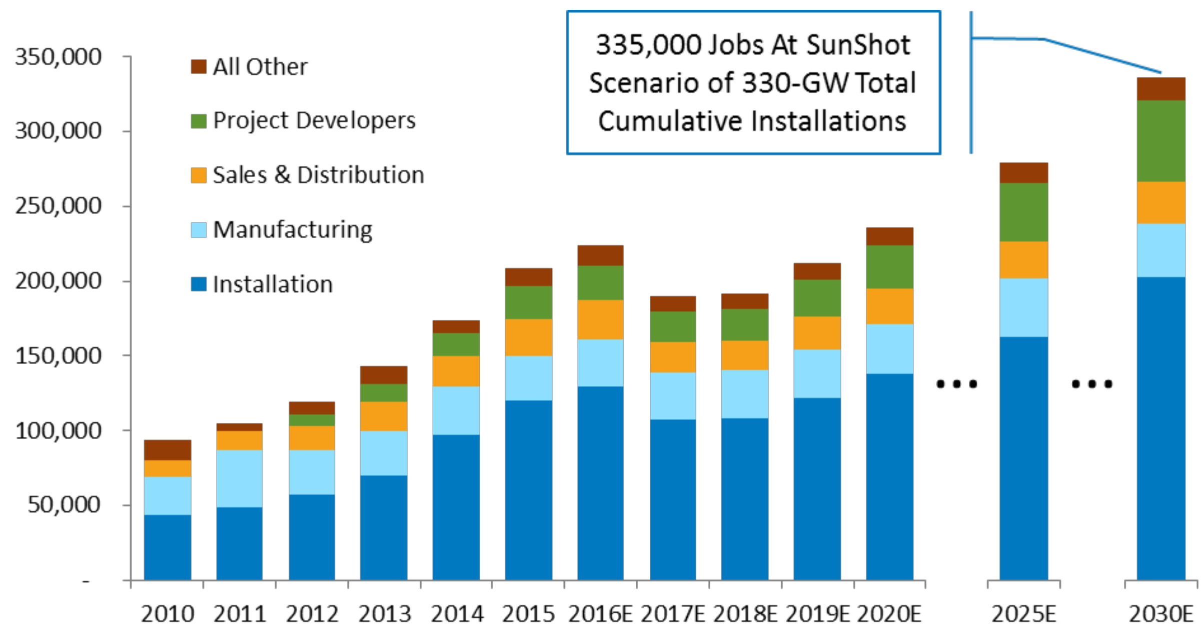

Figure 24. Actual and estimated total solar employment (CSP and PV) by function

Data from The Solar Foundation 2015 and NREL estimates

This methodology ties job projections very closely to expected demand going forward. As such, total solar employment is expected to reach 220,000 jobs in 2016, with a slight drop thereafter caused by the former expectation of an ITC step down in 2017[17]. Manufacturing jobs are not affected as sharply, as these are manufacturing capacity-driven, and we assume that capacity grows at it its historic 3% CAGR[18] from 2015 through 2030. While employment is thus modeled to drop slightly in 2017, solar jobs are expected to again surpass 220,000 in 2020. If the industry progresses toward the SunShot modeled deployment targets of 330 GW of cumulative installed capacity by 2030, the solar industry could grow to directly employ over 335,000 workers.

[16] We sum the MW nameplate capacities (or the approximate equivalent in the case of polysilicon production) across all segments of the value chain to arrive at a total manufacturing capacity in any year.

[17] Although the 30% ITC for solar projects was extended through 2019 in December 2015, the previously anticipated drop had caused a large amount of project demand to be pulled forward into 2016. It is expected that much of this pipeline will still be built in 2016, with recent market forecasts (GTM Research 2015) still expecting a 2016 demand spike followed by slight demand contraction in 2017, with steady demand growth subsequently resuming between 2018 and 2020.

[18] Three percent CAGR observed between 2010 and 2014

3 Concentrating Solar Power (CSP)

After decades of stagnation, U.S. CSP deployment began growing again in the 21st century, while Spain became the world's dominant market for a time. The CSP supply chain supporting this resurgence is primarily composed of plentiful commodity materials such as steel, aluminum, and glass, which can often be sourced within the domestic market where generating plants are constructed. Some specialty components are required for CSP plants—including reflectors, mirror panels, and receiver tubes—but these components comprise only about 11% of total system installed costs. Only a few companies and countries, including the United States, have developed the capacity to supply such specialty components.

CSP manufacturing faces challenges globally and in the United States. Particularly compared with PV, CSP systems are much more complex and require a much larger minimum effective scale, resulting in significantly higher total CAPEX requirements for system construction, lengthier development cycles, and ultimately higher costs of energy produced. These CSP characteristics also favor large, well-funded manufacturers and can bar new disruptive startups. In addition, the global lack of consistent CSP project development creates planning, scale-up, and operational challenges for companies that manufacture specialty CSP components. Finally, the potential lack of a near-term U.S. market is a formidable challenge to domestic CSP manufacturers. Challenging project economics have stalled or spurred the cancellation of many U.S. CSP projects, and declining PV costs have influenced the switch of some large solar projects from CSP to PV. A lack of strong domestic CSP demand in the next five years makes any near-term expansion of U.S.-based CSP production unlikely.

That said, several opportunities exist for U.S. CSP manufacturing in the global and domestic arenas. CSP deployment is expected to grow in regions like China, Africa, and the Middle East over the next several years, followed by potential rapid growth beyond 2020. One projection suggests the United States could lead the world in 2050 with about 230 GW of cumulative CSP capacity. The United States could also benefit from the same innovation advantages it possesses with regard to PV. Significant additional innovation, commercialization efforts, decreases in cost and market development are needed for CSP to become competitive with other generating technologies. Further, development of TES and IPH applications could enhance CSP's unique benefits (Kurup and Turchi 2015b). Established U.S. R&D centers contribute to a strong CSP-specific innovative capacity and knowledge base, which could confer advantage to U.S.-based firms should domestic demand markets recover.

Estimates of potential direct job creation due to CSP installations are included in the total solar employment estimates provided earlier in this report (total solar employment could reach 335,000 jobs by 2030). However, CSP installations can also create significant employment across several supporting commodity industries, due to the commodity-intensive nature of CSP plants. It is estimated that by 2030, CSP could generate up to 33,000 additional jobs across 17 such supporting commodity sectors (e.g., steel, aluminum, glass).

The following sections expand on these points.

3.1 CSP Market Development to Date

Since the 1980s, global CSP deployment has been sporadic and, until 2008, entirely dominated by the United States. The CSP market, however, is on its way to becoming truly global, and the outlines of global commodity and specialty-component supply chains are emerging.

3.1.1 21st Century Resumption of U.S. Growth, Start of Global Expansion

After decades of stagnation, U.S. CSP deployment began growing again in the 21st century, while Spain became the world's dominant market. Figure 25 presents global annual CSP installed capacities from 2007–2014, and estimated installations from 2015 through 2020. For the period 2007–2014, the market grew at a 50% CAGR driven nearly entirely by Spain and the U.S., where 90% of cumulative capacity was installed. Prospects for growth going forward are relatively muted, as new project development in Spain and the U.S. is effectively at a standstill due to the removal or proposed reduction of available subsidies.

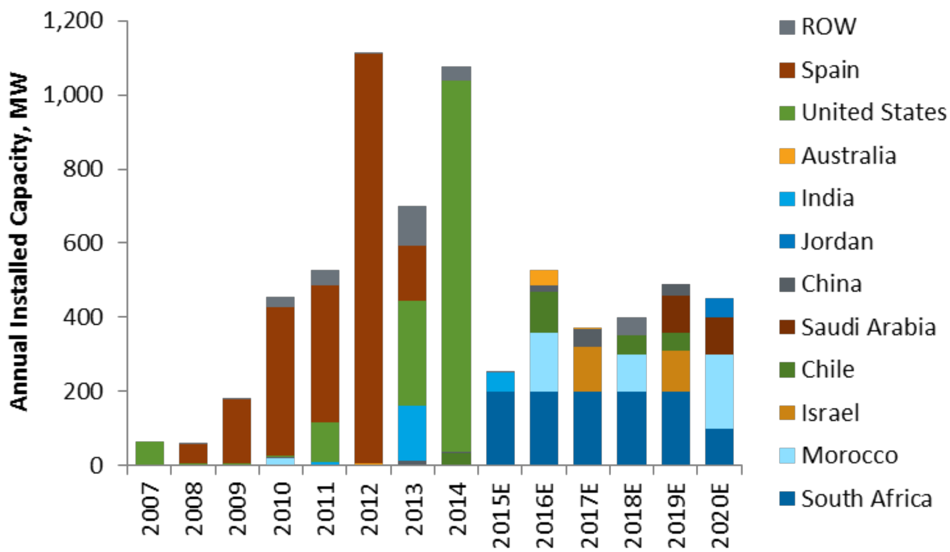

Figure 25. Historical and estimated (E) global annual CSP installed capacity development, 2007–2020

Data from BNEF Desktop Portal 2015

The United States was the first large-scale deployment market for grid-connected CSP. From 1984–1990, 354 MW of total CSP capacity were built at Kramer Junction, California (California Photon 2010). After a period of no further U.S. CSP capacity additions from 1990–2006, the 64-MW Nevada Solar One was completed in 2007 (NREL and SolarPaces 2011b). Beginning in 2010, the United States supported large-scale CSP expansion through a DOE loan guarantee program and the 30% ITC. For example, the 250-MW Mojave project closed a loan guarantee of approximately $1.2 billion (NREL 2012a). Similarly, the 394-MW Ivanpah project received a guarantee for approximately $1.37 billion in debt (Renewable Energy World 2010). From 2012–2015, the ITC and loan guarantees have promoted five new U.S. CSP plants with a cumulative installed capacity of 1,252 MW (DOE 2014).

From 2008–2013, Spain saw the greatest increase in global CSP capacity and, as of 2013, had 50 operational CSP plants totaling 2,300 MW of installed capacity (SolarPaces 2015b). Spain's primary CSP driver was the strong FIT and subsequent FIT increases through the Spanish Royal Decrees 436 and 661 (Climate Parliament 2009). Royal Decree 661 set a capacity target of 500 MW by 2010 and a power purchase agreement (PPA) rate for CSP plants of $0.33/kWh (€0.27/kWh) for 25 years. As a result, Spain produced 2% of its total energy with CSP as of 2014 (SolarPaces 2015b). While Spanish tariffs and support for the CSP industry were strong since 2008, in July 2013 the Spanish government cut all FITs for renewable energy (Alcauza 2013) effectively halting development of substantial new CSP capacity in the country.

3.1.2 Global Commodity Supply Chain

Relatively few comprehensive data exist regarding the CSP supply chain, especially with respect to producers of specialty CSP components (e.g., receiver tubes, mirrors, reflective films). However, recent work by Turchi et al. (2015) has addressed and improved this information gap, documenting the nature, content, and quantity of materials required for typical CSP plants. We highlight this work here and in Section 3.1.3.

Unlike some other renewable energy technologies, in general CSP technologies do not rely on rare earth metals or other materials with potentially restricted supply. Rather, CSP plants are constructed mainly from steel, aluminum, glass, and aggregate materials that are abundant, readily available, and frequently supplied by domestic sources. This is true for most locations in the world where CSP plants might be deployed, and it is an attractive attribute with regard to impacts on the local economy. In the United States, about 90% by mass and 79% by value of the commodity materials used in a 100-MWe CSP plant can be supplied by domestic sources (Turchi et al. 2015).

Over the last few years, PV energy costs have dropped below CSP energy costs, which has shifted CSP's role from being the lowest-cost solar energy provider to being the solar technology capable of providing reliable, dispatch-able, high-value power based on the inclusion of thermal energy storage (TES). TES is critical to the commercial viability of U.S. CSP plants (Turchi et al. 2015), and the increasing number of CSP plants with TES worldwide has increased the importance of solar salt (a mixture of 40% molten potassium and 60% sodium nitrates) in the supply chain.

Material flows for global CSP markets are depicted in Figure 26. Depending on the end market, varying degrees of local sourcing along the chain are possible. For example, the United States can supply much of the raw materials and components needed. In addition, large clusters of CSP-specific manufacturing facilities are generally not needed, because existing non-CSP-specific manufacturing and supply chains are leveraged for most system components and materials. Table 8 shows a snapshot of how some raw materials are refined into components and then used by developers in construction of generating plants.

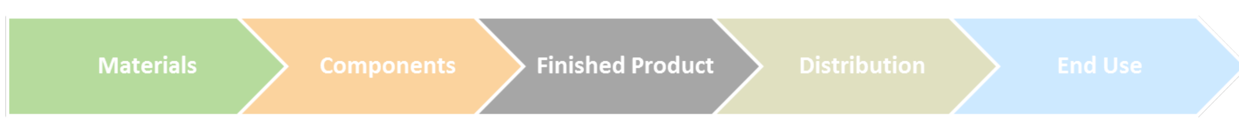

Figure 26. Flow of material to end use for the CSP market

Adapted from Gereffi and Dubay 2009

Table 8. Example of Raw Material Transformation to the End Use for the U.S. CSP Market

Raw Materials for CSP Plants	Components for CSP Plants	Developers and Technology Providers	Owners, Developers, Operators	Utility Company
Steel	Collector Structures	SkyFuel Inc.	Sunray Energy	Southern California Edison
Copper	Mirrors/Reflectors	Acciona Energia	Florida Power & Light	Sierra Pacific Power Co.
Brass	Reflector Film	Sener *(both Developer and Operator)*		Arizona Public Service Co.
Concrete	Heat Collecting Elements (HCEs)/ Receivers	Abengoa Solar[19] *(both Developer and Operator)*		Pacific Gas & Electric Co.
Plastic	Steam Generator	Brightsource *(both Developer and Operator)*		San Diego Gas & Electric
Heat Transfer Fluid (HTF) Synthetic Oil	Balance of Plant	eSolar *(both Developer and Operator)*		Nevada Pwr Co.
Molten Salt	Molten Salt Storage Tanks			
	Field and Central Control Systems			

Adapted from Gereffi and Dubay 2009 and NREL analysis

Figure 27 maps commodity inputs to specific CSP components. The United States has established industries supplying many of the commodities needed (e.g., chemicals, metals, and plastics), although it does not produce solar salt. Instead, Chile produces over 95% of global solar salt supply from areas such as the Atacama Desert. Nonetheless, supply availability is likely not a limiting factor for the U.S. or global CSP industry. SQM, one of the largest producers of molten salt, can produce approximately 1 million MT of salts per year (SQM 2014)—sufficient to supply eight large CSP plants such as Solana[20] annually, which is currently the largest CSP molten salt plant with a 250 MW_{ac} power rating and approximately 5,000 MWh of TES (NREL and SolarPACES 2015b). Table 9 identifies key domestic and foreign-domiciled raw materials suppliers, CSP developers, and CSP component suppliers with U.S. operations.

[19] Abengoa had just begun preliminary insolvency proceedings at the time of this writing.
[20] Solana uses approximately 125,000 MT of molten salt (Parkinson 2013).

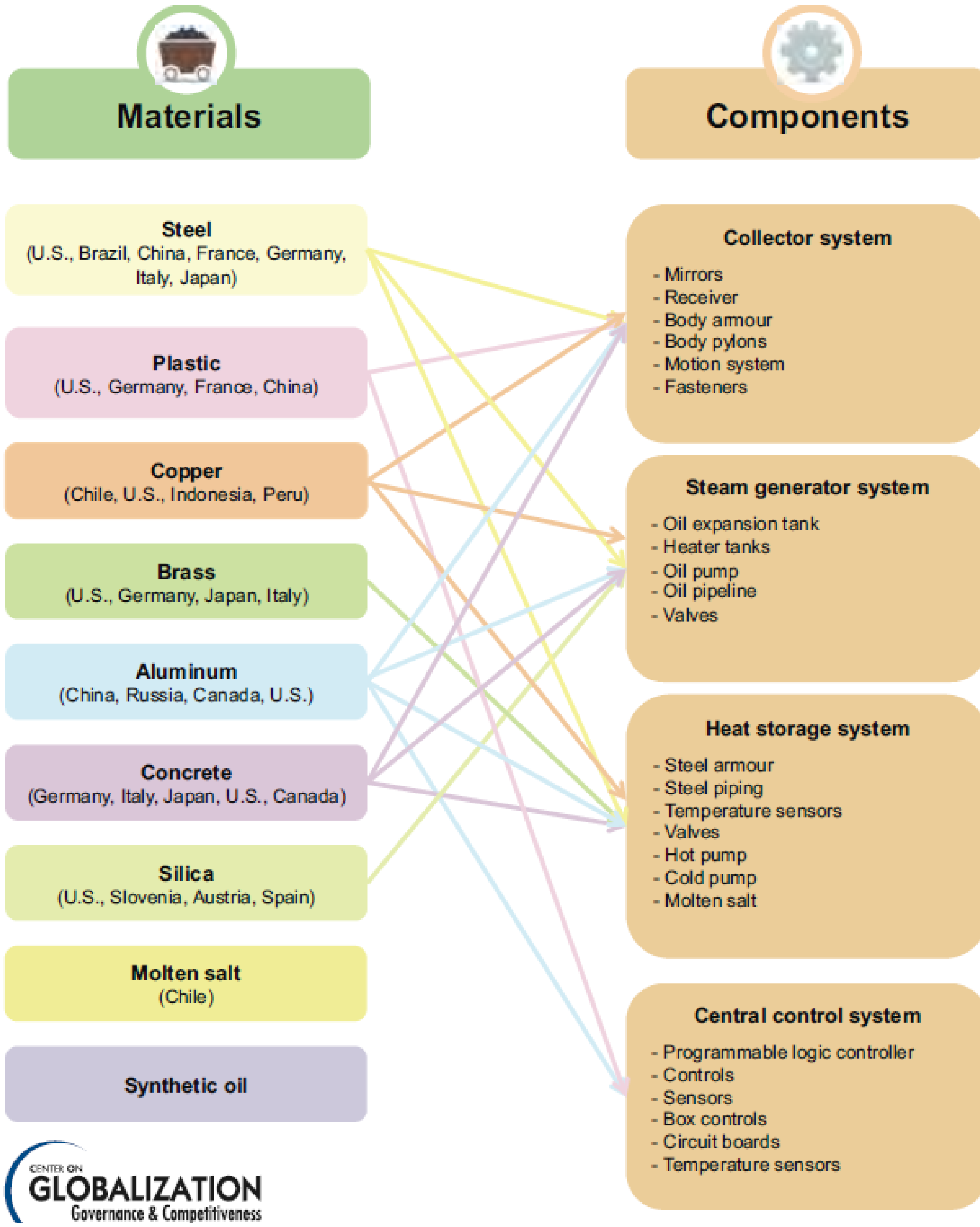

Figure 27. Raw materials used for CSP components and countries with inherent strengths

Reproduced with permission from Gereffi and Dubay 2009, Figure 4-3

Table 9. Supply Chain for CSP Materials and Component Suppliers in the U.S. Market

Primary Raw Materials	Raw Material Suppliers[a]	CSP Components	CSP Component Suppliers	CSP Integrators/ Developers/EPCs
Steel and Stainless Steel	• Nucor • US Steel • AK Steel • Commercial Metals	Piping Pumps Tanks Heat Exchangers	• Alstom Power • Babcock & Wilcox • Bertrams Heatec (Switz.) • Foster Wheeler	• Abengoa/Abeinsa[c] • Acciona • ACS Cobra • Alstom Power • AREVA • Bechtel Corp. • BrightSource Energy • eSolar/GE • Florida Power & Light • Lauren Engineers & Constructors • NextEra Energy • SolarReserve • WorleyParsons
		Receiver Tubes	• Schott (Germany) • Huiyin (China) • Rioglass (Belgium)[b]	
		Solar field frames	• Abengoa (Spain)[b] • AREVA (France) • Gossamer • SENER (Spain) • eSolar • BrightSource • SolarReserve	
Alloy steel	• Special Metals • Haynes • Rolled Alloys	Turbine components	• Alstom (Switz.)[b] • General Electric • SIEMENS (Germany)[b]	
Aluminum	• Alcoa • Century Aluminum • Ormet Primary Alum. • Noranda Aluminum	Solar field frames Cladding	• SkyFuel	
Concrete	Suppliers nationwide	Foundations Tower		
Glass	• Guardian • RioGlass (Belgium)[b] • Saint-Gobain (France)[b] • Flabeg (Germany)	Mirrors	• 3M • Guardian • RioGlass (Belgium)[b] • Saint-Gobain (France)[b] • Flabeg (Germany) • SkyFuel[b]	
Silver	• Teck Alaska • Hecla Mining • Kennecott Utah • U.S. Silver • Newmont Mining	Reflectors		
Copper	• Freeport-McMoRan • Kennecott Utah • ASARCO	Reflectors Power system		
Nitrate Salt	• SQM (Belgium) • BASF (Germany)[b]	HTF TES media	• SQM • Yara Salts	

[a] Top domestic raw material producers/suppliers listed, unless noted
[b] Have U.S. manufacturing facilities
[c] Abengoa had just begun preliminary insolvency proceedings at the time of this writing.

Data from Turchi et al. 2015

This list is a first attempt to uncover the identity and number of potential suppliers for commodity materials needed for CSP component and plant production. Until further detailed investigations are conducted, including extensive collaboration with CSP developers, it is unlikely that a more exact list of material and component suppliers can be determined for U.S. CSP plants.

At the time of this writing, the United States has no local content requirements for CSP components or plants. While many CSP components and raw materials are readily available from U.S. sources, discussions with industry indicate that importing certain items may prove more cost effective. Still, many materials used are likely sourced domestically. For example, in developing the Solana project, Abengoa Solar estimated that 73% of the equipment supplied would be of U.S. origin (Maracas 2011).

3.1.3 Limited Specialty Component Supply Chain

CSP specialty components such as receiver tubes, mirror panels, and reflective thin polymer films are manufactured in custom facilities that require fixed investments to build. Given the small size of today's global CSP market, only a few companies and countries have developed the capacity to supply such specialty components. While a comprehensive, up-to-date listing of such CSP component manufacturing facilities is unavailable, Table 10 presents some known facilities to suggest the current scale and locations as well as the CAPEX required where data are available.

Table 10. CSP Specialty Component Manufacturers

Company	Component	Locations	Capacity and Cost	Data Source
Schott Solar	Receiver tubes for parabolic troughs	Spain and Germany	~600 MW combined p.a.	Interview with Schott Solar (2015)
Flabeg FE	Mirror panels for parabolic troughs	Germany	~400 MW p.a.	Flabeg FE (2015)
Rioglass	Mirror panels for parabolic troughs and power towers	U.S., Spain, South Africa, Chile, Israel, China	U.S.: 900,000 mirrors p.a. (~280 MW p.a.); $50 million CAPEX	O'Grady (2011); Atlas Copco (2015); Rioglass (2015)
Reflectech Plus	Thin film reflective polymer for parabolic troughs	U.S.	120,000 panels p.a. (~150 MW)	Kurup and Turchi (2015a); NREL (2012)
SkyFuel	Mirror panels using Reflectech Plus films and specialized support ribs for parabolic troughs	U.S.	120,000 mirrors p.a. (~150 MW p.a.); 470,000 ribs p.a. (~50 MW p.a.);	Skyfuel (2015a and 2015b)

The United States has only one specialized manufacturing facility for the thin film reflective polymer film Reflectech Plus, a product developed by SkyFuel and NREL as a lightweight, highly reflective alternative to the mirror panels most commonly used in parabolic trough plants

(NREL 2012). Reflectech Plus is laminated to 0.05-in-thick aluminum panels to become a slide-able mirror panel, at present used in the SkyTrough parabolic trough (Kurup and Turchi 2015a). Other companies, such as Gossamer and 3M, are also developing reflective, thin film polymers with Sandia National Laboratories and NREL, though these are yet to have commercial application (Molnar and O'Neill 2015). Figure 28 shows the precision rib assembly machine and the Reflectech Plus manufacturing setup.

Figure 28. SkyFuel aluminum parabolic rib assembly machine and Reflectech Plus manufacturing

Relatively Small, Declining CSP Specialty Costs

The cost structure for CSP systems is dominated by commodity construction materials (e.g., steel, concrete, aluminum, plastic) and installation labor, with relatively smaller portions of total system value coming from specialized CSP components (e.g., mirrors/reflectors, reflector film, collectors, receivers).

NREL recently estimated the installed cost of a representative CSP parabolic trough plant in Arizona, with a 100-MWe solar field (large enough to accommodate 6 h of molten salt TES), parabolic troughs, and synthetic HTF (Kurup and Turchi 2015a). This study updated earlier cost benchmarking (Turchi 2010). The latest NREL reference plant now assumes air cooling rather than wet cooling and assumes use of the SkyTrough aluminum spaceframe design with the thin film polymer reflectors (Reflectech Plus) as shown in Figure 29. The figure shows the front and back (i.e., spaceframe) of one SkyTrough module, or solar collector element (SCE). Modules are built up to make solar collector assemblies (SCAs), and loops of SCAs make up a solar field. For reference, 1,500 SCAs were used for the representation, with each SCA having a net aperture area of 656 m^2.

Figure 29. SkyTrough module front and back used to create NREL CSP cost model

Source: Kurup and Turchi 2015a

We review the reference plant cost breakdown to clarify the contribution of specialty components to system installation costs.[21] We use design and manufacturing analysis to determine the dimensions, material, manufacturing processes, and specific steps needed to convert raw materials to finished components. Cost estimates assumed components were manufactured at commercial volumes by established facilities. The installed cost was based on a mix of estimates from technology developers, NREL modeled manufacturing costs, actual quotes from component suppliers, and construction cost estimating techniques.

Figure 30 shows the installed cost per square meter of aperture area for a 1,500-SCA solar field (approximately 950,000 m^2), which can provide the thermal input to a 100-MWe CSP plant with 6 h of TES. The installed solar field cost is approximately $\$170/m^2$. Solar field assembly labor (embedded in the costs shown in Figure 30) constitutes less than 10% of the solar field installed cost. The installation of specialty CSP components (mirror panels, receivers, and parabolic ribs for the SkyTrough) constitutes $\$71/m^2$, with roughly 90% or $\$63/m^2$ of this being product cost. When multiplied by the aperture area for the representative plant, this results in a specialty product cost of $61 million. Further markups for sales tax, overhead, and contingencies totaling 23% are next applied to arrive at a fully loaded specialty component cost of $75 million.

Compared to the overall CSP installation costs for the representative plant of $6,700/kWe or $670 million, specialty components thus make up about 11% of the total system installed costs, despite constituting a large portion of solar field costs. This suggests a potentially less intense focus on first costs concerning such specialty products, possibly enabling manufacturers to compete on factors beyond price. In contrast, solar PV modules comprise approximately 36% of total installed cost for a utility-scale PV system, and all PV specialty components (PV modules, inverters, and mounting systems) together comprise over 50% of total PV system installed costs (Chung et al. 2015). The resulting impacts of this cost pressure on PV component manufacturers is documented earlier in this report.

[21] Including EPC costs only—development costs, such as land entitlement and environmental permitting are not included.

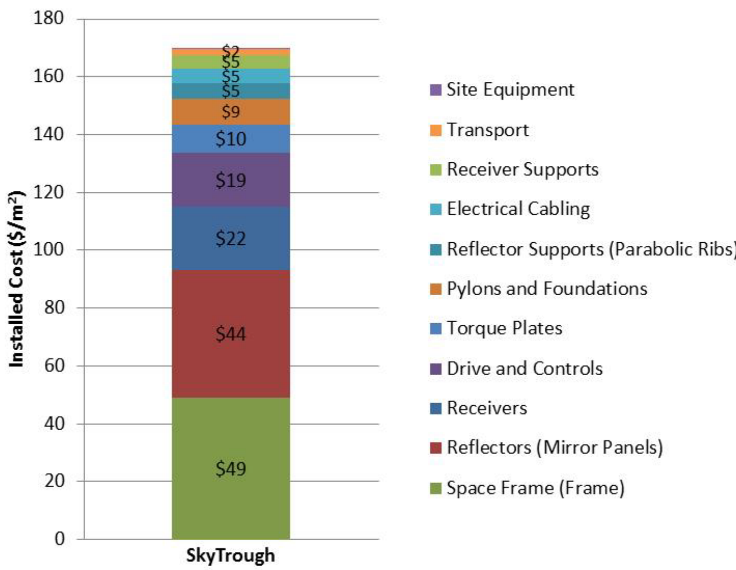

Figure 30. Installed Solar Field cost per square meter for SkyTrough assuming 1,500 SCAs (total = $170/m^2$)

Data from Kurup and Turchi 2015a; does not include development costs, such as land acquisition or entitlement

Solar field costs are also impacted by the volatility in commodity prices and global commodity dynamics. For example, the modeled SkyTrough installed cost would rise from $170/m^2$ to nearly $210/m^2$ if the aluminum alloy cost was $1.70/lb instead of $1.03/lb (Kurup and Turchi 2015a). The manufacturing location for specific components such as the steel structures (as reflected by industry practices) also made a significant difference in the overall modeled installed cost, with a nearly 30% savings realized from sourcing Indian fabricated steel structures (e.g., galvanized pylons) than from U.S. market suppliers. Further analysis on foreign commodity pricing affecting U.S. competitiveness has yet to be undertaken.

3.2 CSP Challenges

CSP faces many challenges globally and in the United States. These include the technology's large effective scale and relatively high complexity and cost, inconsistent annual demand for CSP systems, and uncertain near-term growth prospects.

3.2.1 Large Scale, High Complexity, High Cost

The most critical challenges to CSP deployment revolve around CSP's competition with conventional and other renewable generation technologies and the implications for all-in system development and installation costs. Particularly compared with PV, CSP electricity systems are much more complex to develop, design, construct, and operate, and they require a much larger minimum effective scale (generally 50–100 MWe minimum, compared with cost-effective residential PV systems as small as 3 kW). This large scale and complexity result in typically lengthier development cycles, much higher total CAPEX requirements for project development, system construction, and relatively higher costs of energy produced.

Global competition within the CSP industry is characterized by a few well-funded companies or large parent companies that have created CSP firms focused on project development. Most CSP developers (e.g., Abengoa Solar previously and Sener) are vertically integrated companies with capabilities spanning from R&D through EPC. The large capital requirements to develop and deploy CSP technologies at commercial scale can bar new disruptive energy startup companies. For example, one large recent CSP project (the recently commissioned Crescent Dunes 110-MWe power tower plant, with 10 hours of molten salt storage), had an estimated CAPEX of approximately $980 million (SNL 2014).

Today's main specialty component manufacturers, such as Schott Solar and Flabeg FE, have developed expertise by leveraging existing core competencies of a parent company. For example, Schott has a long history in the glass industry and, with the combined R&D support from the German government, developed a leading position in CSP receiver tubes. Flabeg FE was spun out of Flabeg GmbH, one of the biggest mirror and glass producers in Germany. These specialty manufacturers have typically developed processing and tooling in-house, and they generally do not purchase "turnkey" manufacturing lines from capital equipment suppliers, as is observed in the PV industry. As a result, knowledge flows in CSP component manufacturing are more restricted, potentially enhancing firms' abilities to retain and fully capitalize on proprietary knowledge stocks developed internally, but also potentially restricting manufacturing capacity growth and scale-up.

3.2.2 Inconsistent Annual Demand

For specialty manufacturers serving the sector, the high minimum scale for generating systems creates particular challenges. Demand can be volatile owing to the small size of the industry, the lengthy development cycles, and the large project sizes relative to total market size. This volatility is reflected in the year-on-year total industry growth rates shown in Figure 31. The industry installs small numbers of large-capacity projects on an inconsistent basis, making manufacturing capacity planning, scale-up, and efficient operation difficult.

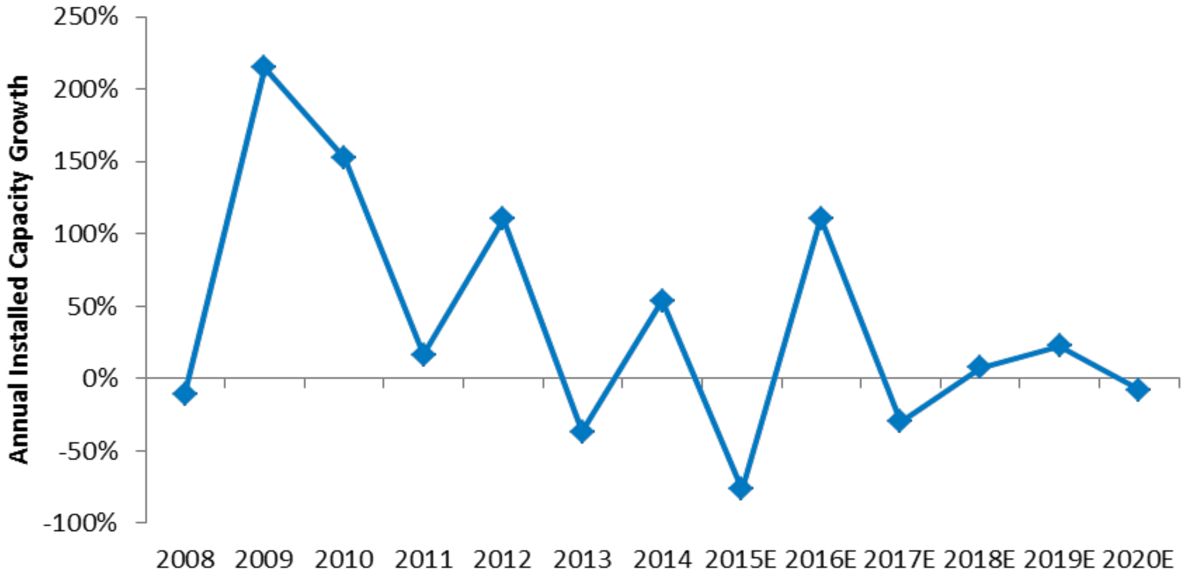

Figure 31. Year-over-year change in annual CSP installations

Data from BNEF Desktop Portal 2015

3.2.3 Uncertain Near-Term U.S. Growth Prospects

For U.S.-based manufacturing, the potential lack of a steady, large near-term domestic market is also a formidable challenge. Many U.S. CSP projects have recently stalled or been abandoned, including Palen Solar Holdings (500-MWe), BrightSource (750-MWe), and Rice Solar Energy Project (150-MWe), given challenging economics and long development cycles (NREL 2013a; NREL 2013b; Kraemer 2014). The declining cost of PV has also impacted CSP acceptance and deployment, at current PV grid penetrations (Hill 2015). This has been a major factor influencing several large projects to transition from CSP to PV technologies (Mehos et al. 2016).

3.3 U.S. CSP Opportunities

Despite the many challenges, several opportunities exist for U.S. CSP manufacturing. These include strong global and U.S. long-term growth potential as well as U.S. advantages in CSP innovation.

3.3.1 Global Near- and Long-Term Growth Potential

Global CSP market demand and potential growth for the next five years is expected to be somewhat flat, with approximately 7 GW of cumulative installed capacity expected by 2020 (Figure 32). However, while expected annual installations will be smaller than in recent years, installations are expected to be steadier, and demand is also expected to diversify: South Africa, Morocco, Israel, Chile, and Saudi Arabia are among the regions expected to see CSP growth through 2020.

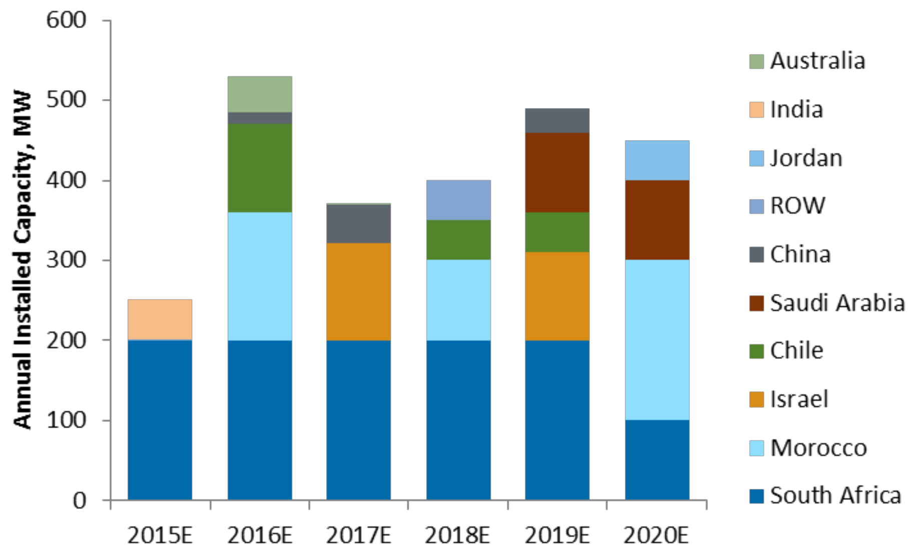

Figure 32. CSP installed capacity forecast by region through 2020

Data from BNEF Desktop Portal 2015

Each key current CSP market faces specific near-term challenges and drivers, which are summarized in Table 11.

Table 11. Select Drivers and Challenges Faced in Key Global CSP Markets through 2018

Market	Drivers	Challenges
United States	• Large pipeline of projects under development and planning	• Significant price pressure competing with low-cost PV and low grid rates
China	• 5 Year Plan deployment targets	• Resources are far from demand areas
Saudi Arabia	• Excellent DNI resource	• Uncertainty regarding needed political support
India	• Ambitious CSP targets under National Solar Mission	• 15%–20% lower DNI than predicted for first round of plants
Morocco	• Excellent DNI	• Cost of financing
South Africa	• Storage mandated as part of tenders • PPA price multiplier of 2.7x for CSP plants meeting the 5-h evening peak (SolarPaces 2015a)	• Cost of financing
Chile	• Reportedly best DNI conditions (e.g., > 3,200 kWh/m^2/year) (CSP Today 2013)	• Lack of water availability • CSP competing with fossil fuels

Data from IEA (2014b)

Beyond 2020, global CSP growth is expected to be much more rapid, and CSP with TES is expected to become a major renewable energy contributor in certain regions. As shown in Table 12, by IEA estimates the United States is expected to lead cumulative CSP installed capacity, with approximately 230 GW by 2050. While SunShot estimates for U.S. installed capacity are more conservative by comparison, they nonetheless represent a substantial increase over deployments today (cumulative 1.8 GW). For the United States, the future basis and need for CSP with TES for electricity may be driven by higher PV and wind penetrations (Mehos et al. 2016) whose variability could increase demand for more dispatchable energy sources.

Table 12. Potential Growth of CSP through 2050 across Major CSP Regions

	SunShot	IEA							
	U.S.	**U.S.**	**E.U.**	**China**	**India**	**Africa**	**Middle East**	**ROW**	**Total**
2030	28	87	15	29	34	32	52	12	261
2050	83	229	28	118	186	147	204	71	983

Data from IEA 2014b and DOE 2012

3.3.2 U.S. Innovation Advantages

With respect to CSP component manufacturing, if the U.S. market demand outlook recovers, some of the same positive competitiveness factors that apply to the PV industry (Section 2.3) should also apply to CSP.

Significant opportunities exist for CSP cost reductions through innovation, and even the basic technological paradigm (parabolic trough vs. power tower) has not been settled. While traditional parabolic trough CSP systems have been in operation for some time, their unsubsidized cost of energy is not yet competitive with incumbent generating sources in many markets. Thus, as with PV, innovations in CSP target a lower LCOE through lower installed costs, higher system efficiencies, or both. However, TES innovations unique to CSP enable energy production during times of greater value to the grid and thus potentially higher compensation rates compared with rates for a non-dispatchable resource such as PV (Mehos et al. 2016). The development of power tower plants with direct molten salt storage has aimed to improve the cost and TES aspects of CSP.

The high levels of innovation needed to drive costs down favor nations such as the United States that consistently rank highly on measures of general innovative capacity. Further, the United States has built significant CSP-specific knowledge stocks, especially in relation to competing nations. The United States accounted for 38% of cumulative global CSP patents between 1976 and 2006, compared to 20% for Japan, the next-highest single nation. Interestingly, while Spanish and German firms are currently key CSP component suppliers and project developers, their patenting activities account for only 0.9% and 2.2%, respectively, of total filings over this period (Figure 33).

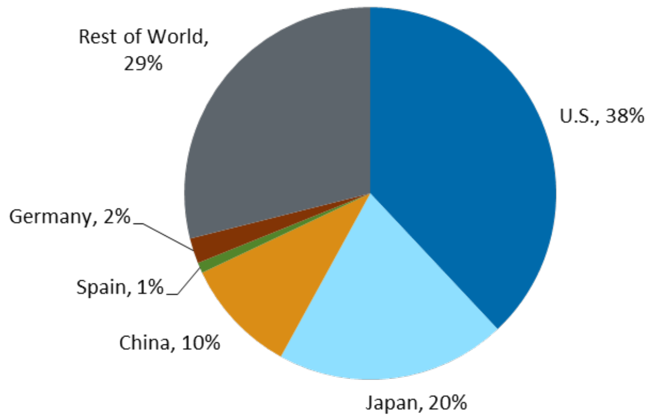

Figure 33. Share of CSP patent counts by country from 1976–2006

Data from SBC Energy Institute 2013

The United States is also home to several R&D centers (e.g., Sandia National Laboratories and NREL) with a history of CSP-related research portfolios. Such R&D centers and firms developing and commercializing CSP technologies could mutually benefit from increased linkages and knowledge flows arising from close proximity.

3.3.3 U.S. CSP Job Estimates

Job scenarios presented in Section 2.3.3 also include direct jobs created by the CSP industry. Using SunShot estimates of expected deployment by 2030 (302 GW of PV and 28 GW of CSP), a total of 335,000 PV and CSP jobs could be expected in that year.

CSP plants also require large amounts of commodity materials in their construction, on the order of 190,000 MT of materials across approximately 17 key commodities (e.g., steel, aluminum, glass, crushed aggregate) for a 100-MWe plant. Due to the this high commodity content, Turchi et al. (2015) examined the job impacts of CSP plants upon commodity producing industries. Within the commodity industries studied, approximately 1.6 direct jobs per MW_e are required to produce the inputs needed, with another 3.3 indirect jobs needed per MW_e. Assuming these same intensities hold in 2030, the installation of CSP plants could account for an additional 33,000 jobs across the key commodity input sectors.

References

Alcauza, Jorge. 2013. "Spain Kills Feed-in Tariff for Renewable Energy." CSP-World. July 13. http://www.csp-world.com/news/20130713/001121/spain-kills-feed-tariff-renewable-energy.

Altman, Edward. 1968. "Financial Ratios, Discriminant Analysis and the Prediction of Corporate Bankruptcy." The Journal of Finance XXIII (4): 589–609.

Anand, Mohit. 2015. "Global PV Manufacturing Attractiveness Index 2015 (PVMAX)." Market Research Report. GTM Research.

Ashta, Arvind. 2008. "Sustainable Growth Rates: Refining a Measure." Strategic Change 17 (5-6): 207–14. doi:10.1002/jsc.827.

Atlas Copco. 2015. "Generating Power from the Sun Is Recharging the Arizona Economy." Atlas Copco. Accessed November 19. http://www.atlascopco.us/Images/Rioglass%20Solar_tcm45-3577633.pd.

Bakewell, Sally. 2011. "Chinese Renewable Companies Slow to Tap $47 Billion Credit," November 16. http://www.bloomberg.com/news/articles/2011-11-16/chinese-renewable-companies-slow-to-tap-47-billion-credit-line.

Barbose, Galen, John Miller, Ben Sigrin, Emerson Reiter, Karlynn Cory, Joyce McLaren, Joachim Seel, Andrew Mills, Naïm Darghouth, and Andrew Satchwell. 2016. *On the Path to SunShot: Utility Regulatory and Business Model Reforms for Addressing the Financial Impacts of Distributed Solar on Utilities*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65670. http://www.nrel.gov/docs/fy16osti/65670.pdf.

Basore, Paul A., Donald Chung and Tonio Buonassisi. 2015. "Economics of Future Growth in Photovoltaics Manufacturing." presented at the IEEE Photovoltaic Specialists Conference, New Orleans, LA, June 19. http://www.nrel.gov/docs/fy15osti/64487.pdf.

Bloomberg L.P. 2015. "Financial Data from Bloomberg Database."

Bloomberg New Energy Finance (BNEF). 2015. "Bloomberg New Energy Finance Desktop Portal." Accessed November 9. www.bnef.com.

Carr, Mike. 2015. "The 2015 Solar Jobs Census, EERE's Solar Program & SunShot Initiative." presented at the Environmental and Energy Study Institute and The Solar Foundation Government Briefing: "Find Out How Many Solar Jobs Were Created in Your State," Washington, D.C., March 2. http://www.eesi.org/files/Mike_Carr_030215.pdf.

Chung, Donald, Carolyn Davidson, Ran Fu, Kristen Ardani, and Robert Margolis. 2015. "U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential, Commercial, and Utility-Scale Systems." NREL/TP-6A20-64746. Golden, CO: NREL. September. http://www.nrel.gov/docs/fy15osti/64746.pdf.

Chung, Donald, Kelsey Horowitz, and Parthiv Kurup. 2016. *On the Path to SunShot: Emerging Opportunities and Challenges in U.S. Solar Manufacturing*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-65788. http://www.nrel.gov/docs/fy16osti/65788.pdf.

Climate Parliament. 2009. "Feed-In Tariffs Support Solar Thermal Power in Spain." Climate Parliament. http://www.e-parl.net/eparliament/pdf/080603%20Solar%20thermal%20toolkit.pdf.

De la Tour, Arnaud, Matthieu Glachant, and Yann Ménière. 2011. "Innovation and International Technology Transfer: The Case of the Chinese Photovoltaic Industry." Energy Policy 39 (2): 761–70. doi:10.1016/j.enpol.2010.10.050.

De la Tour, Arnaud, Matthieu Glachant, and Yann Ménière. 2013. "Predicting the Costs of Photovoltaic Solar Modules in 2020 Using Experience Curve Models." Energy 62 (December): 341–48. doi:10.1016/j.energy.2013.09.037.

Deloitte (Deloitte Touche Tohmatsu Limited and The U.S. Council on Competitiveness (Deloitte). 2013. "Global Manufacturing Competitiveness Index 2013." http://www2.deloitte.com/content/dam/Deloitte/global/Documents/Manufacturing/gx_2013%20Global%20Manufacturing%20Competitiveness%20Index_11_15_12.pdf.

DOE (U.S. Department of Energy). 2012. "SunShot Vision Study." Washington, DC: U.S. Department of Energy. DOE/GO-102012-3037. http://www.nrel.gov/docs/fy12osti/47927.pdf.

DOE (U.S. Department of Energy). 2014. "2014: The Year of Concentrating Solar Power." DOE. http://energy.gov/sites/prod/files/2014/05/f15/2014_csp_report.pdf.

DOJ (U.S. Department of Justice). 1992. "Horizontal Merger Guidelines." U.S. Department of Justice. April 2. http://www.justice.gov/atr/horizontal-merger-guidelines-08192010.

Duetch, John, and Edward Steinfeld. 2013. "A Duel in the Sun: The Solar Photovoltaics Technology Conflict between China and the United States." Massachusetts Institute of Technology. https://mitei.mit.edu/system/files/201305-futureofsolar-SunDuel.pdf.

Earth Policy Institute. 2014. "Annual Solar Photovoltaics Module Production by Country, 2007-2013, with Projection to 2017." Earth Policy Institute Data Center. June. http://www.earth-policy.org/data_center/C26.

EIA (U.S. Energy Information Administration). 2015. "Electric Power Monthly, Table 5.6.A. Average Price of Electricity to Ultimate Customers by End-Use Sector, by State, August 2015 and 2014." http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

Endres, Martin. 2015. Discussions with Schott Solar.

ENF. 2013. "Market Survey: Chinese Cell and Panel Manufacturers, 6th Edition." Market Research Report. ENF Business Consulting (Wuhu) Co., Ltd., August.

Feldman, David, and Mark Bolinger. 2016. *On the Path to SunShot: Emerging Opportunities and Challenges in Financing Solar*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65638. http://www.nrel.gov/docs/fy16osti/65638.pdf.

Flabeg FE. 2015. "Flabeg Contact." Accessed November 19. http://www.flabeg-fe.com/en/contact.html.

Fraunhofer ISE. 2014. "Fraunhofer ISE Photovoltaics Report." Freiburg: Fraunhofer Institute for Solar Energy Systems ISE.

Fu, Ran, Ted L James, Donald Chung, Douglas Gagne, Anthony Lopez, and Aron Dobos. 2015. "Economic Competitiveness of U.S. Utility-Scale Photovoltaics Systems in 2015: Regional Cost Modeling of Installed Cost ($/W) and LCOE ($/kWh)." pp. 1–11. IEEE. doi:10.1109/PVSC.2015.7356261.

Gambhir, Ajay, Rob Gross, and Richard Green. 2014. "The Impact of Policy on Technology Innovation and Cost Reduction: A Case Study on Crystalline Silicon Solar PV Modules." London Imperial College. http://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/working-papers/The-impact-of-policy-on-technology-innovation-and-cost-reduction-WP.pdf.

Gan, Peck Yean, and ZhiDong Li. 2015. "Quantitative Study on Long Term Global Solar Photovoltaic Market." Renewable and Sustainable Energy Reviews 46 (June): 88–99. doi:10.1016/j.rser.2015.02.041.

Gereffi, Gary, and Kristen Dubay. 2009. "Concentrating Solar Power - Clean Energy for the Electric Grid." Center on Globalization Governance and Competitiveness. http://www.cggc.duke.edu/environment/climatesolutions/greeneconomy_Ch4_ConcentratingSolarPower.pdf.

Gouras, Eckhart. 2014. "More Private Enterprise." PV Magazine, March. http://www.pv-magazine.com/archive/articles/beitrag/more-private-enterprise-_100014462/618/#axzz3qa2p34G4.

Grace, Amy, and Nathan Serota. 2015. "Yes, US Clean Energy, There Is a Santa Claus." Analyst Reaction. Bloomberg New Energy Finance.

Grau, Thilo, Molin Huo, and Karsten Neuhoff. 2012. "Survey of Photovoltaic Industry and Policy in Germany and China." Energy Policy 51 (December): 20–37. doi:10.1016/j.enpol.2012.03.082.

GTM Research. 2015. "GTM Preliminary US PV Forecast." GTM Research, December 16.

Honeyman, Cory, Shayle Kann, Leandra Cooper, MJ Shiao, Nicole Litvak, Jade Jones, Tom Kimbis, Justin Baca, Shawn Rumery, and Aaron Holm. 2015. "U.S. Solar Market Insight Report - Q1 2015 - Full Report." Market Research Report. GTM Research and the Solar Energy Industries Association (SEIA).

International Energy Agency (IEA). 2014a. “Technology Roadmap, Solar Photovoltaic Energy. 2014 Edition.” Paris.

International Energy Agency (IEA). 2014b. “Technology Roadmap - Solar Thermal Electricity 2014 Edition.” International Energy Agency (IEA). http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarThermalElectricity_2014edition.pdf.

Isoard, Stéphane, and Antonio Soria. 2001. “Technical Change Dynamics: Evidence from the Emerging Renewable Energy Technologies.” Energy Economics 23 (6): 619–36. doi:10.1016/S0140-9883(01)00072-X.

James, Adam S. 2015. “Global PV Demand Outlook, 2015-2020: Exploring Risk in Downstream Solar Markets.” Market Research Report. GTM Research.

Jones-Albertus, Rebecca, David Feldman, Ran Fu, Kelsey Horowitz, and Michael Woodhouse. 2015. “Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity.” Submitted to Progress in Photovoltaics, September. http://energy.gov/sites/prod/files/2015/10/f27/LCOEConsiderations_101915.pdf.

Jones, Jade. 2015. “Global PV Price Outlook 2015.” Market Research Report. GTM Research.

Kobos, Peter H., Jon D. Erickson, and Thomas E. Drennen. 2006. “Technological Learning and Renewable Energy Costs: Implications for US Renewable Energy Policy.” Energy Policy 34 (13): 1645–58. doi:10.1016/j.enpol.2004.12.008.

Kraemer, Susan. 2014. “The Future of ITC and CSP in the USA.” CSP Today. April 25. http://social.csptoday.com/markets/future-itc-and-csp-usa.

Kurup, Parthiv, and Craig Turchi. 2015a. “Parabolic Trough Collector Cost Update for the System Advisor Model (SAM).” NREL/TP-6A20-65228. Golden, CO: NREL. November. http://www.nrel.gov/docs/fy16osti/65228.pdf.

Kurup, Parthiv, and Craig Turchi. 2015b. “Initial Investigation into the Potential of CSP Industrial Process Heat for the Southwest United States.” NREL/TP-6A20-64709. Golden, CO: NREL. November. http://www.nrel.gov/docs/fy16osti/64709.pdf.

Labastida, Roberto Rodriguez, and Dexter Gauntlett. 2015. “Distributed Solar PV: Market Drivers and Barriers, Technology Trends, Competitive Landscape, and Global Market Forecasts.” Market Research Report. Boulder, CO: Navigant Consulting, Inc.

Luo, Lu. 2011. “China’s Polysilicon and Wafer Makers Forge Ahead.” Research note. Bloomberg New Energy Finance.

Manyika, James, Jeff Sinclair, Richard Dobbs, Gernot Strube, Louis Raaey, Jan Mischke, Remes Jaana et al. 2012. “Manufacturing the Future: The next Era of Global Growth and Innovation.” McKinsey Global Institute and McKinsey Operations Practice.

Maracas, Kate. 2011. "Solana Generating Station." Arizona Energy. http://www.azenergy.gov/doclib/6-3-11%20Solana%20Generating%20Station.pdf.

Mehos, Mark, Craig Turchi, Jennie Jorgenson, Paul Denholm, Clifford Ho, and Kenneth Armijo. 2016. *On the Path to SunShot: Advancing Concentrating Solar Power Technology, Performance, and Dispatchability*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-65668. http://www.nrel.gov/docs/fy16osti/65668.pdf.

Mints, Paula. 2015. "Photovoltaic Manufacturer Capacity, Shipments, Price & Revenues." Market Research Report SPV-Supply3. SPV Market Research.

Molnar, Attila, and Mark O'Neill. 2015. "Advanced Reflective Films and Panels for next Generation Solar Collectors." EERE. http://www1.eere.energy.gov/solar/sunshot/pdfs/csp_review_meeting_042313_molnar.pdf.

Nemet, Gregory F. 2006. "Beyond the Learning Curve: Factors Influencing Cost Reductions in Photovoltaics." Energy Policy 34 (17): 3218–32. doi:10.1016/j.enpol.2005.06.020.

NREL. 2012a. "DOE Finalizes $1.2 Billion Loan Guarantee for Mojave Solar Project." NREL Concentrating Solar Power Research. February 15. http://www.nrel.gov/csp/news/2011/1591.html.

NREL. 2012b. "NREL and SkyFuel Partnership Reflects Bright Future for Solar Energy." NREL Technology Transfer. April 19. http://www.nrel.gov/technologytransfer/ss_jorgensen.html.

NREL and SolarPACES. 2011a. "Power Tower Projects." NREL Concentrating Solar Projects. May 13. http://www.nrel.gov/csp/solarpaces/power_tower.cfm.

NREL and SolarPACES. 2011b. "Nevada Solar One." NREL Concentrating Solar Projects. September 7. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=20.

NREL and SolarPACES. 2013a. "Rice Solar Energy Project." NREL Concentrating Solar Projects. January 30. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=61.

NREL and SolarPACES. 2013b. "Palen Solar Electric Generating System." NREL Concentrating Solar Projects. April 4. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=53.

NREL and SolarPACES. 2015a. "Xina Solar One." NREL Concentrating Solar Projects. April 14. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=275.

NREL and SolarPACES. 2015b. "Solana Generating Station." NREL Concentrating Solar Projects. August 19. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=23?print.

NREL and SolarPACES. 2015c. "Crescent Dunes Solar Energy Project." NREL Concentrating Solar Projects. November 10. http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=60.

O'Grady, Patrick. 2010. "Rioglass Solar Brings Manufacturing Plant to Surprise." Phoenix Business Journal. August 11. http://www.bizjournals.com/phoenix/stories/2010/08/09/daily36.html.

Parkinson, Giles. 2013. "World's Largest Solar Thermal Plant With Storage Comes Online." Clean Technica Power. October 14. http://cleantechnica.com/2013/10/14/worlds-largest-solar-thermal-plant-storage-comes-online/.

Pillai, Unni. 2015. "Drivers of Cost Reduction in Solar Photovoltaics." Energy Economics 50 (July): 286–93. doi:10.1016/j.eneco.2015.05.015.

Porter, Michael E. 1979. "How Competitive Forces Shape Strategy." Harvard Business Review. https://hbr.org/1979/03/how-competitive-forces-shape-strategy.

Provaggi, Alessandro. 2013. "China Development Bank's Financing Mechanism: Focus on Foreign Investments." https://gpc.stanford.edu/sites/default/files/uc07_0.pdf.

Quitzow, Rainer. 2015. "Dynamics of a Policy-Driven Market: The Co-Evolution of Technological Innovation Systems for Solar Photovoltaics in China and Germany." Environmental Innovation and Societal Transitions, January. doi:10.1016/j.eist.2014.12.002.

Renewable Energy World. 2010. "Brightsource Offered US $1.4B DOE Loan Guarantee for Ivanpah Project." Renewable Energy World. February 23. http://www.renewableenergyworld.com/articles/2010/02/brightsource-offered-us-1-4b-doe-loan-guarantee.html.

Rioglass. 2015. "Rioglass Locations." Rioglass Locations. Accessed November 19. http://www.rioglass.com/?page_id=1518.

SBC Energy Institute. 2013. "CSP Factbook." Schlumberger Business Consulting. http://www.sbc.slb.com/SBCInstitute/Publications/~/media/Files/SBC%20Energy%20Institute/SBC%20Energy%20Institute_Solar_Factbook_Jun%202013.ashx.

SEMI. 2015. "International Technology Roadmap for Photovoltaic (ITRPV): 2014 Results." 6th Edition. Berlin, Shanghai, Zhubei, and San Jose: SEMI.

SkyFuel Inc. 2015a. "SkyFuel Manufacturing Mirror Panels." SkyFuel. http://www.skyfuel.com/mirror-panels.shtml.

SkyFuel Inc. 2015b. "SkyFuel Manufacturing Parabolic Precision Rib." SkyFuel. http://www.skyfuel.com/rib-assembly.shtml.

SNL (Sandia National Laboratories). 2014. *Crescent Dunes Solar Energy Project*. *DOE Global Energy Storage Database*. July 17. http://www.energystorageexchange.org/projects/348.

SolarPACES. 2015a. "Country Information South Africa." http://www.solarpaces.org/country-information/south-africa.

SolarPACES. 2015b. "Country Information Spain." solarPACES. http://www.solarpaces.org/country-information/spain.

SQM. 2014. "SQM's Thermo-Solar Salts: The Natural Solution for Thermal Storage and Heat Transfer in Your CSP Plant." SQM.

Sun, Honghang, Qiang Zhi, Yibo Wang, Qiang Yao, and Jun Su. 2014. "China's Solar Photovoltaic Industry Development: The Status Quo, Problems and Approaches." Applied Energy 118 (April): 221–30. doi:10.1016/j.apenergy.2013.12.032.

The Solar Foundation. 2016. "National Solar Jobs Census 2015." http://www.thesolarfoundation.org/wp-content/uploads/2016/01/TSF-2015-National-Solar-Jobs-Census.pdf. Accessed 1/12/2016.

Turchi, Craig. 2010. "Parabolic Trough Reference Plant for Cost Modelling with the Solar Advisor Model (SAM)." NREL. http://www.nrel.gov/docs/fy10osti/47605.pdf.

Turchi, Craig, Parthiv Kurup, Sertac Akar, and Francisco Flores. 2015. "Domestic Material Content in Molten-Salt Concentrating Solar Plants." NREL/TP-5500-64429. Golden, CO: NREL. http://www.nrel.gov/docs/fy15osti/64429.pdf.

Wang, Xiaoting. 2014. "The Relentless Fall in Chinese Module Costs." Research Note. Bloomberg New Energy Finance.

Wang, Xiaoting. 2015. "Chinese Government Picks PV Manufacturing Winners." Research Note. Bloomberg New Energy Finance.

Watanabe, C., A. Nagamatsu, and C. Griffy-Brown. 2003. "Behavior of Technology in Reducing Prices of Innovative Goods—an Analysis of the Governing Factors of Variance of PV Module Prices." Technovation 23 (5): 423–36. doi:10.1016/S0166-4972(01)00121-3.

Wiser, Ryan, Trieu Mai, Dev Millstein, Jordan Macknick, Alberta Carpenter, Stuart Cohen, Wesley Cole, Bethany Frew, and Garvin A. Heath. 2016. *On the Path to SunShot: The Environmental and Public Health Benefits of Achieving High Penetrations of Solar Energy in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65628. http://www.nrel.gov/docs/fy16osti/65628.pdf.

Woodhouse, Michael, Rebecca Jones-Albertus, David Feldman, Ran Fu, Kelsey Horowitz, Donald Chung, Dirk Jordan, and Sarah Kurtz. 2016. *On the Path to SunShot: The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65464. http://www.nrel.gov/docs/fy16osti/65464.pdf.

World Economic Forum. 2014. "The Global Competitiveness Report: 2014-2015." Insight Report. Switzerland. http://www3.weforum.org/docs/WEF_GlobalCompetitivenessReport_2014-15.pdf.

Yu, C.F., W.G.J.H.M. van Sark, and E.A. Alsema. 2011. "Unraveling the Photovoltaic Technology Learning Curve by Incorporation of Input Price Changes and Scale Effects." Renewable and Sustainable Energy Reviews 15 (1): 324–37. doi:10.1016/j.rser.2010.09.001.

Zhao, Xin-gang, Guan Wan, and Yahui Yang. 2015. "The Turning Point of Solar Photovoltaic Industry in China: Will It Come?" Renewable and Sustainable Energy Reviews 41 (January): 178–88. doi:10.1016/j.rser.2014.08.045.

Zheng, Cheng, and Daniel M. Kammen. 2014. "An Innovation-Focused Roadmap for a Sustainable Global Photovoltaic Industry." Energy Policy 67 (April): 159–69. doi:10.1016/j.enpol.2013.12.006.

Zhi, Qiang, Honghang Sun, Yanxi Li, Yurui Xu, and Jun Su. 2014. "China's Solar Photovoltaic Policy: An Analysis Based on Policy Instruments." Applied Energy 129 (September): 308–19. doi:10.1016/j.apenergy.2014.05.014.

Appendix: PV Cost-Reduction Drivers

We use previous studies of PV cost drivers to inform our original analysis of cost-reduction drivers. Like many other researchers (Table 13), we focus on price, because reliable cost data are not widely available. We recognize, however, that this is not ideal when exploring the impact of various factors on cost as non-cost-related factors, such as supply-demand imbalances and the concentration of market players, have large impacts on price that are independent of the production cost.

FigureA-1 shows the major inputs affecting c-Si PV module price. The lines with a single arrow indicate a hypothesized causal relationship, while the lines with an arrow on each end represent a hypothesized non-causal relationship. It is important to hypothesize justifiable causal relationships, because it is easy to mistake correlation for causation in analyzing the past contributions to cost reductions. The τ symbols in FigureA-1 represent relationships where we would expect a time delay. For example, investments in R&D, even at the company level, do not directly translate to the implementation of new ideas and thus a change in module prices. Prices may be more immediately affected if a company increases its gross margin to cover R&D spending, so we might also expect an immediate impact of company R&D spending on price, but companies' margins are often set by what the market demands rather than what is required to cover fixed costs at any given point in time.

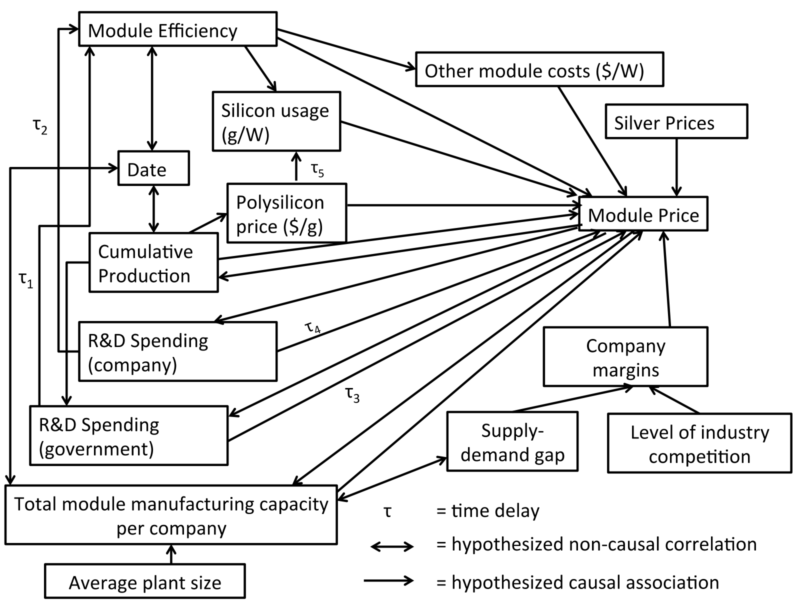

Figure A-1. Major factors influencing c-Si module price

As the figure shows, many factors influence module price, and the relationships between these inputs can be complex, including feedback mechanisms and time lags. Many studies have predicted future module prices using a one-factor learning curve (price versus cumulative production), but this approach is subject to omitted variable bias and provides little insight into actual price-reduction drivers (Yu et al. 2011). Further, sensitivity to the specific periods studied can have a significant impact on the predictive results.

Recognizing these limitations, several researchers have used alternative approaches to understanding PV price (Table 13). The most common approach, employed in all studies in Table 13 except Nemet (2006) and Isoard and Soria (2001), is multivariable regression or multifactor learning curve analysis. Not all these studies, however, include the same variables in their models. Generally, researchers have included either: (1) cumulative capacity, scale, and input prices; or (2) cumulative capacity and cumulative knowledge stock. Knowledge stock is represented by either patent activity or R&D expenditures that are typically modeled as a depreciating input value with a time lag. The former studies (1) find cumulative capacity and silicon prices to be the most important factors in fitting the historical price curves with low error, and the latter studies (2) find cumulative capacity and knowledge stock both play an important role. Studies that additionally include scale (usually plant size) also find that scale has a statistically significant relationship to price. Several studies additionally find a large (sometimes the largest) impact from remaining factors not explicitly included in their regression models; what these remaining factors include is generally not well understood.

Across the studies reviewed, it is clear that learning-by-doing, scale, polysilicon prices, and knowledge stock/innovation have played important roles in reducing PV prices. However, because the different variables included in each study all produce statistically significant results, the degree of importance of any single factor is difficult to surmise. The variables studied are often highly correlated, and many different combinations of variables could result in a regression with a high R^2 value.

One challenge in analyzing historical contributions to cost reduction is that while results may become more reliable with a greater number of data points (years), there also tends to be distinct, relatively short periods in PV development with different characteristics. Consistently throughout the literature the relative importance of the different factors discussed depends on the period in the technology's development, and this indicates we could expect different trends in future periods. Typically, two to three distinct historical stages are discussed:

- **1970s–mid-1980s**. Innovation and R&D investment played a critical role. PV became more focused on terrestrial applications, and competition and standardization were beginning to be introduced.
- **Late 1980s–early 2000s**. Average commercial module efficiencies improved dramatically (c-Si modules), and capacity began to expand rapidly to meet growing demand bolstered by government incentives and subsidies.
- **2000s**. Period characterized by swings in polysilicon prices and reduced silicon use, globalized manufacturing and competition, periods of strong oversupply, the increasing importance of multicrystalline silicon, and decreasing government support.

Table 13. Summary of PV Module Price Studies Reviewed

Study (Year)	Period Analyzed	Variables Included	Main Drivers Suggested	Possible Issues and Comments
C.F. Yu (2011)	1976–2006	• Cumulative production • Plant size • Silicon price • Silver price	1976–1986 (negative residual) • Remaining factors • Silicon price • Cumulative production (learning) 1987–1997 (positive residual) • Remaining factors • Silicon price 1998–2006 (positive residual) • Cumulative production • Silicon price	• Remaining factors are the largest contributor to price reductions in all periods except 1998–2006, and these are largely unknown • Moderate to severe collinearity of the input variables (judged by VIF)
Gan and Li (2015)[22]	1988–2006	• Silicon price • Cumulative production • Supply-demand gap • Chinese share in the global PV market	• Silicon price • Cumulative production	• Learning rate declines over time (authors suggest this is because of reduced technology change as products/industry mature)
Kobos et al. (2006)	1975–2000	• R&D with a time lag and depreciation (i.e., "knowledge stock") • Cumulative production	• Cumulative production has slightly greater impact on price than knowledge stock, but both are significant over this period	• Global R&D data assumed. Also assumes perfect diffusion internationally + correlation of R&D activities with industrial solar cell designs • Omitted variable bias • VIF is large (9.073) • Results highly sensitive to the time lag and knowledge depreciation
de La Tour (2013)	1990–2011	• Cumulative production • Silicon price • Silver price • R&D (discounted stock of patent families) • Plant size	• The case with just silicon prices and cumulative production produced the result with the lowest error	• R&D knowledge stock data only go through 2007
Watanabe (2003)	1976–1995, Japanese prices and production only	• Feedback between knowledge stock (R&D), prices, capacities, cumulative production, relative energy price	• Best R^2 for economies of scale and learning, although high R^2 for several different possible fits/explanations • Production could be impacted by module price, relative energy price, and technology knowledge stock (which can be impacted by different kinds of R&D)	• Claim changes are triggered by a specific project just by using the regression analysis (claim causality without strong evidence) • Omitted variable bias • Statistics for things like multicollinearity not provided • Only a few firms • Specific to Japan

[22] The study regresses over this full period 1988–2006 and then also regresses separately over 1988–1996, 1997–2001, and 2002–2006. The study also performs several regressions including different sets of the input variables listed.

Study (Year)	Period Analyzed	Variables Included	Main Drivers Suggested	Possible Issues and Comments
Isoard and Soria (2001)	1976–1994	• Installed capacity • Production scale	• Installed capacity and production scale both predict price with statistical significance • Learning-by-doing and returns to scale both important, but are technology specific and vary over the course of technology-development phases	• Omitted variable bias • Potential issues of lag
Pillai (2014)	2005-2012	• Efficiency • Silicon consumption (g/W) • Plant Size • Annual industry capital expenditures • Annual firm capital expenditures • Cumulative industry output • Polysilicon price • Market share of Chinese firms	• Polysilicon price • Polysilicon usage • Total annual industry investment (posited mechanism is economies of scale in the capital equipment) • Efficiency	• Overestimation of the impact of polysilicon usage versus efficiency by using g/W • Correlation between variables unspecified • Many different regressions give good fits
Nemet (2006)	1975–2001	• Module efficiency • Plant size • Silicon price • Silicon consumption (g/W) • Yield • Wafer size • Multicrystalline market share vs. monocrystalline	• Module efficiency • Plant size • Silicon price • Other factors	• Overestimation of the impact of polysilicon usage versus efficiency by using g/W
This Analysis (2016)	2005–2015	• Silicon price • Silver price • Average plant size (module, cell, wafer among top 10 firms) • Average total capacity across top 10 firms • Cumulative production • Gross and operating margins, top 10 firms • Government R&D expenditures • Company R&D expenditures, top 10 firms • Module efficiency • Wafer thickness	<u>Single Variable</u> • Efficiency • Cumulative production • Plant size (cell and module) <u>Two Variables</u> • Efficiency + silicon price • Silicon price + cumulative production <u>Extension of Nemet's Methodology, 2005–2015</u> • Plant size • Other factors • Efficiency • Silicon price	• High correlations between variables in single-factor models, with many factors showing good fits • Multicollinearity in multi-factor models • Relative price reduction impact of factors, or combinations of factors, cannot be discerned

Between 2005 and 2015, c-Si module designs and manufacturing processes have been mature, with only incremental modifications to the standard technology. This period has also been characterized by fierce competition along the supply chain, large capacity expansions, trade barriers, and fluctuating supply-demand conditions that have driven large changes in polysilicon, wafer, cell, and module prices. We conducted a multivariable regression over this most recent 10-year period, examining results with all possible subsets of the following inputs:

- Silicon price
- Silver price
- Average module plant size, cell plant size, or wafer plant size across the top-10 PV companies
- Average total capacity across the top 10 PV companies for wafer, cells, or modules
- Cumulative production
- Company margins (gross and operating)
- Total government R&D investment (global, U.S., or China)
- Total R&D investment for the top 10 c-Si PV manufacturers
- Average commercial module efficiency
- Wafer thickness.

Data are drawn from Bloomberg L.P. (2015), Fraunhofer ISE (2014), SEMI (2015), Gambhir et al. (2014), the London Metal Exchange, and Mints (2015), with all price data adjusted to be in 2015 U.S. dollars.

We find that, when a single variable is examined, statistically significant results with a high R^2 (above 0.89) can be obtained when fitting to efficiency, cumulative production, average module plant size, or average cell plant size (statistically significant results for the influence of each input variable, $p < 0.05$). The highest R^2 (0.96) for a one-factor model is found for average module plant size. The fact that good fits can be obtained with any of these factors is explained by the high correlations between these variables over this period, suggesting that any one-factor model over these years—while potentially providing statistically significant results—cannot determine which factor (efficiency, scale, or learning-by-doing) actually had the greater impact on cost. Because of these correlations between important variables, and the limited number of data points (9–10) available over this period, trying to resolve this problem by introducing additional variables produces multicollinearity issues: while a very high R^2 can be obtained, the statistical significance of any one variable in explaining the price changes is lost. Still, we obtained statistically significant results with a low variance inflation factor (VIF) with two-factor models that included silicon price and efficiency, or silicon price and cumulative production. These results largely mirror results from earlier studies, in that they identify a handful of key drivers (silicon price, cumulative production, plant size, efficiency) but cannot discriminate the relative impacts among them.

Nemet attempted to solve some of the potential problems associated with the regression analyses discussed above by analyzing PV price reductions with an engineering model that analytically quantified the impacts of specific actions, such as improving module efficiency, reducing silicon use, and increasing wafer size. Nemet (2006) finds that plant size, module efficiency, and polysilicon prices have had the largest impact on module prices, in that order. However, there are some potential issues with this approach. Thus, we modify Nemet's methodology to mitigate these issues (see Appendix A.1).

Using this modification to Nemet's methodology, we re-analyze price-reduction factors for 1975-2001, and we conduct new analysis for the period 2005–2015 (Section A.1 details the modifications). We find that plant size, other factors, module efficiency, and silicon prices had the greatest impact during 1975–2001, in that order. These results are similar to the results of the original paper. Plant size remains one of the most influential inputs over a wide range of potential scaling factors (Section A.1 details the scaling factor), but its order of importance changes with changes in the scaling factor, and uncertainty on this point remains. Learning-by-doing (associated with cumulative production) or learning-by-searching (associated with innovation and R&D) may contribute to the "other factors."

For 2005–2014, we find that, for scaling factors down to 0.055 (0.18 was used in the original Nemet model, based off our some results in other semiconductor industries), plant size has the largest impact. For all scaling factors up to 0.29 (which is very high compared to what has been observed in other industries), we obtain a negative residual, defined in the Nemet analysis as the difference between the actual price changes observed and those predicted by summing up all the contributions from variables included in the analysis. This residual is greater than $0.50/W for scaling factors of 0.18 or larger. While the exact value of this is imprecise based on how we estimated the total influence of the inputs (averaging the year-by-year impact), we conclude that other factors, including learning-by-doing or learning-by-searching, still had a significant impact on price over this later period. We find that, for this period, the factors with the greatest impact were plant size, other factors, efficiency, and silicon price, in that order. The literature cited in Table 13 provides additional discussion on driving factors, market conditions, and periods of development in the PV industry.

For additional insight into innovation's role in driving down PV costs, we document the significant changes in design or processes adopted by the c-Si industry over time. FigureA-2, from Gambhir et al. (2014), summarizes these changes. Until the 1990s, more significant innovations in process and design along the supply chain were implemented. Since 2000, very few significant changes to the overall design or manufacturing process for Al BSF cells—which are still dominant in the marketplace—have been made. Instead, innovations have taken the form of incremental improvements within existing technologies, such as continuing to increase yields, reduce material use/waste, increase automation and wafer size, and raise efficiency with small improvements in material quality, optical efficiency, and passivation. Precisely identifying the origins of such improvements is difficult. Some, such as improved yield and material quality via better process control, likely derive from learning-by-doing within factories and firms. Others could result from firm learning-by-searching (R&D), and we find that corporate R&D is a better predictor of average commercial c-Si module efficiencies than silicon price, module price, or global (U.S., Chinese, and German) government R&D spending on PV (via a multiple regression analysis with the inputs specified in FigureA-1). Combined, these types of innovations have had a substantial impact on cost, even in the more recent period during which each individual change would be associated with relatively small cost reductions or efficiency improvements.

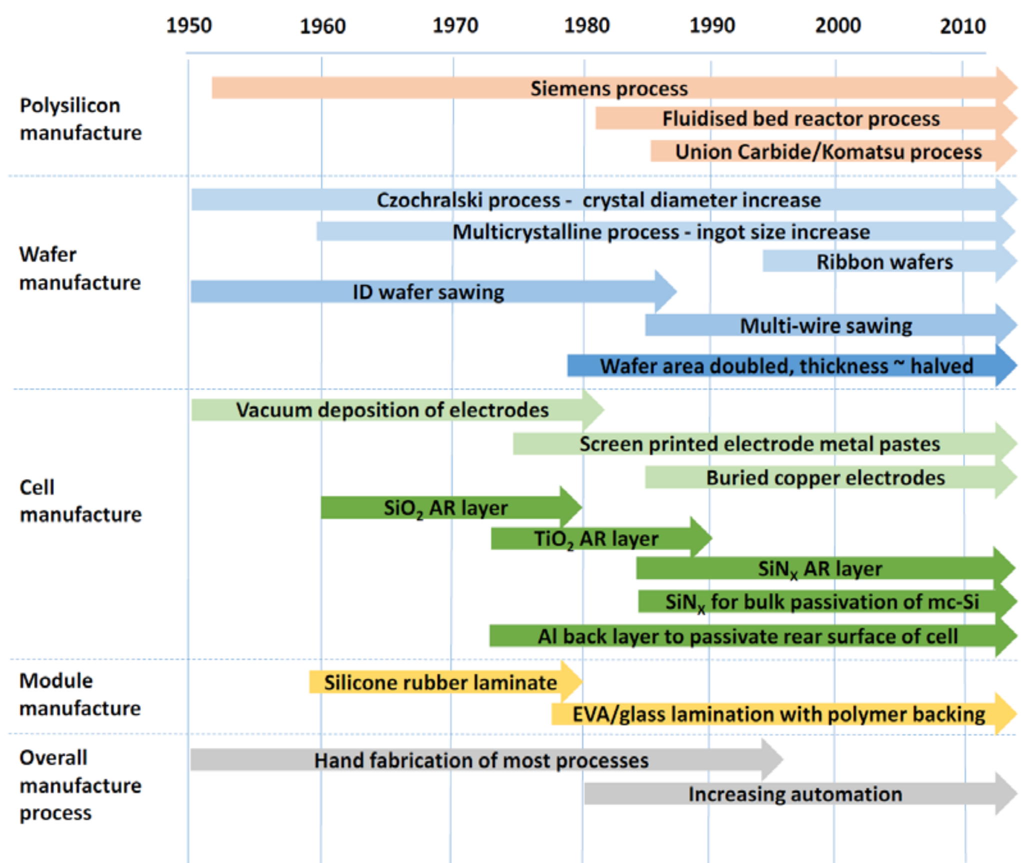

Figure A-2. Historical changes in c-Si PV technology

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In figure, Al = aluminum, AR = anti-reflective, EVA = ethylene-vinyl acetate, ID = inner diameter, mc = microcrystalline, N = nitrogen, O = oxygen, Si = silicon, and Ti = titanium.

Modification to Nemet's Methodology

While we adopt Nemet's (2006) approach to clarify key drivers of PV module price reductions for the period 2005–2014 via an engineering approach, we modified several parts of the methodology. The original model essentially is a sensitivity analysis, which examines the potential impact on module price of changing a given input variable from its starting value in 1975 to its ending value in 2001, starting with the module price in 1975. However, because the input variables are changing simultaneously and module prices are being reduced (for the most part) every year during this period, the sensitivity of module price to any given input is lower in every year after 1975 than it in is 1975, and it is significantly lower in 2001. For example, in analyzing the period 1975–2001, Nemet's formula for computing the impact of polysilicon price reductions on module price is:

$$\Delta C_{t(SC)} = (SC_t \text{ x } SU_{t-1}) - (SC_{t-1} \text{ x } SU_{t-1}),$$

where $\Delta C_{t(SC)}$ is the change in module price attributable to silicon price reductions, SC_t is the silicon price in 2001, SC_{t-1} is the silicon price in 1975, and SU_{t-1} is the silicon utilization in 1975.

Because module cost changes due to SC at any time are equal to SC_t x SU_t, the sensitivity of module cost at any given time is simply SU_t, but Nemet uses SU_{t-1} (the silicon utilization in 1975), which is the highest value over this period, to compute total reductions due to silicon price over the full analysis period. This same type of issue arises for other input variables, ultimately overestimating their contribution and underestimating the unexplained residual.

Additionally, the original model inputs silicon consumption in terms of grams per watt, which is itself dependent on module efficiency, which is also included as a separate variable in the analysis. This means the impact of efficiency is essentially accounted for twice.

Finally, the original paper also uses a scaling model from the semiconductor industry, which is similar in many ways to solar but dissimilar in others, and for which a wide variety of scaling factors have been found in the literature depending on the specific technology, period of analysis, and other factors. The estimate for the impact of scale on module price is highly sensitive to this scaling factor, and thus a significant amount of uncertainty is introduced via this variable. However, a better alternative does not appear to currently exist for estimating scale, because there is essentially no literature on PV that separates out the scaling or plant size impact or total company capacity from the impact of learning and experience based on cumulative production.

For these reasons, we adopt the following changes to the original methodology:

- Use silicon wafer thickness, rather than silicon consumption in grams per watt, as an input variable to decouple the interrelations between grams-per-watt consumption and efficiency.
- Compute the partial derivatives of module price with respect to different variables (except for scale and multicrystalline silicon share) for each year in an attempt to more accurately understand the total contribution to price reductions over this period. The impact of the change in input variable from 1975–2001 is computed for each annual time step and then summed to compute the total change over this period.
- Explore the sensitivity of the results to the scaling factor. The factor has meaningful impacts on the results, but few data are available to inform the appropriate value to use with respect to the PV industry.