Executive Summary

Solar power is undergoing a revolution. Over the past decade, an energy source as old as the planet and theoretically all but limitless has plummeted in cost and begun in some places to be harnessed in large volume. This dynamic is disrupting the modern energy system and, as energy disruptions always do, rattling the geopolitical order. In the process, the industry that produces the equipment to convert sunlight into electricity is simultaneously reeling, consolidating, and surging. These twin transformations—one of the global energy system, one of the global solar industry—carry profound implications for national economies and for the planet. At the center of both transformations sits China.

The New Solar System illuminates key and little-understood changes that are remaking the solar enterprise—in China and thus in the world. Based on this analysis, it recommends changes in U.S. solar policy—particularly timely with a new U.S. administration and Congress—that would put solar power on a more economically sensible path toward environmentally significant growth.

A Global Solar Strategy: Harnessing Comparative Advantage to Cut Solar's Cost

Solar power has grown massively in recent years and yet it still represents only about 1% of global electricity generation. Mainstream observers now predict that solar photovoltaic could provide 16% of global electricity by mid-century, and credible sources predict even higher levels.

Whether solar power grows this significantly, and whether in the process it makes much environmental difference, will depend in large part on whether governments approach it with a new level of economic efficiency. Many of the solar policies that countries have adopted thus far have been inefficient. They have achieved, to varying degrees, their stated goals of boosting domestic solar manufacturing or deployment in the near term, but often they have done so in ways that are unable to be sustained—for political or economic reasons or both.

The result, in much of the world, has been wild swings in solar policy, ranging from unnecessarily generous support to unreasonable neglect. That has contributed to a boom-bust pattern in the solar industry that has benefited no one: not investors, solar-technology entrepreneurs, ratepayers, taxpayers, or citizens around the world who could benefit from an energy system decarbonized sooner rather than later. Enabling solar power to scale to a level that can help curb fossil-fuel emissions requires governments to find smarter means of policy and financial support. One key predicate for making smarter policy is taking into account a country's relative comparative advantage in the rapidly globalizing solar industry: what it does well and what it does not.

The New Solar System does not seek to enable any country to beat another in the global solar industry. It seeks instead to help all countries find their most effective places. By better understanding and playing to their comparative strengths in the solar business, countries would achieve two key objectives. They would reduce the cost for the world of scaling up solar power. And they would be better positioned to fashion policies that maximized the long-term benefit to their own economies from solar's global growth.

It is important to be clear: This notion of comparative advantage is no rose-colored vision of borderless global harmony. It is the increasing reality of the cutthroat international solar market today. It does not ignore very real tensions between China and the United States, including an ongoing dispute in which each country has imposed solar tariffs on the other, doubts about the protection of intellectual property in China, and concerns by both the U.S. and Chinese governments about national security. Rather, it puts those concerns into perspective, which is

something that investors, corporations, and governments try to do every day.

The Chinese solar industry is likely to remain, for the foreseeable future, the major driver of the global solar industry. But this does not mean that China as a country will remain as dominant in the solar industry as it is now. This distinction—China as the leader of the global solar industry but with declining dominance—is crucial in clarifying the roles that other countries could sustainably play in the global solar industry of the future.

This emphasis on economic efficiency in the globalizing solar industry is particularly relevant during the administration of U.S. President Donald Trump, who has talked approvingly of tariffs against China and who has questioned the desirability of U.S. support for renewable energy and of U.S. action to curb carbon emissions.

The New Solar System is based on some two years of work by Stanford University's Steyer-Taylor Center for Energy Policy and Finance, an initiative of Stanford Law School and Stanford Graduate School of Business. The research was funded by a research grant from the U.S. Department of Energy's (DOE's) Solar Energy Technologies Office. Stanford's Steyer-Taylor Center proposed the research and initiated the grant application to the DOE. The grant provided the center with full independence and authority to frame the inquiry, conduct the research, draw conclusions, and write this report.

Busting Myths About China's Solar Sector

The New Solar System busts five key myths about China's solar industry that have prevailed in the West. Clarifying the reality behind those myths is crucial to charting a more economically efficient path forward for solar power:

***Myth*:** China's solar industry is a financial bubble about to burst.
***Fact*:** Chinese solar companies are reforming their capital structures to make them more economically efficient.

***Myth*:** China doesn't innovate.
Fact: China is innovating significantly in solar—not only in manufacturing processes, China's traditional strength, but also increasingly in underlying solar R&D.

***Myth*:** The global solar industry is centralizing in China.
Fact: The global solar industry, led by Chinese companies, is showing early signs of decentralizing geographically.

***Myth*:** Tariffs imposed by the United States and the European Union are hobbling the Chinese solar industry.
Fact: Tariffs imposed by the United States against imported Chinese solar products are forcing the Chinese solar industry to get leaner and stronger and are failing to achieve a goal articulated strongly by their Western supporters: to catapult the United States into the ranks of the world's major solar manufacturers. Moreover, the U.S. tariffs have prompted China to impose its own tariffs on U.S.-made polysilicon, the solar-manufacturing sector in which the United States traditionally has been most dominant.

***Myth*:** China's solar market is largely closed to foreign investment.
Fact: Top Chinese government officials and corporate executives have concluded that China needs both capital and sophisticated investment structures from the West in order to scale up solar to the point where it would help achieve China's climate targets. Their interest presents a profitable opportunity for players in the West.

The Maturation of China's Solar Enterprise

China's solar enterprise has encompassed three broad stages. First, China commoditized the manufacture of vast quantities of solar equipment. Next, it deployed vast quantities of that equipment within its borders. Now, China is attempting something more subtle and, if it succeeds, more far-reaching: to reform both its solar-R&D effort and its massive solar-deployment apparatus to make them more economically efficient. The R&D reform represents an acknowledgment by the Chinese government that its solar-R&D efforts thus far have been insufficiently productive. The attempt to reform solar deployment is about financial innovation—both in government policy and in private-investor practice. The success of both these shifts will be crucial if the world is to ramp up solar deployment to levels that contribute meaningfully to global climate reductions.

The New Solar System details how the Chinese solar enterprise is evolving across four key dimensions: its financial status, its research-and-development capabilities, its manufacturing prowess, and its deployment of solar projects.

Financial Status

In the near term, the major China-based solar manufacturers are struggling with the repercussions of a strategy they have used essentially since their inception: aggressively expanding manufacturing capacity to increase their global market share. Longer-term, however, the financial condition of the Chinese solar industry, as a group, appears to be improving. Corporate consolidation in the Chinese solar industry is in full swing, yielding a smaller number of larger, stronger, and globalizing players.

Corporate profit margins, though still thin, are rising. Debt, though still high, is becoming less of a concern, both because the extent of leverage of China's major solar manufacturers is lower than it was during the last major industry downturn, in 2012, and because debt is shifting to forms that the Chinese companies are better equipped to shoulder. Government policy support—which initially was, by the admission of top Chinese government officials themselves, wasteful—is being tightened with an eye toward producing more solar deployment for every yuan's worth of subsidy.

Research and Development

The widespread assumption in the West has been that the United States and certain European countries, notably Germany, produce the major technological advances in solar, and that China picks up those technological advances and then figures out how to drive down the cost of manufacturing them at scale. *The New Solar System* largely upends that view. It finds that the Chinese solar industry is producing more underlying technological innovation than the conventional wisdom suggests.

Some of this innovation has put China ahead of the U.S. in certain key solar technologies. In one example, Trina Solar, one of the world's largest solar manufacturers, has become the first China-based firm to be recognized on the U.S. National Renewable Energy Laboratory's well-known chart of solar-cell-efficiency world records. Trina has achieved the world record in the efficiency of a research-scale version of the type of solar cell that dominates the global market: the multicrystalline-silicon cell. China's solar industry is making less, though still notable, progress in several other solar-technology areas.

The New Solar System maps China's solar-R&D ecosystem, providing what the Stanford research team believes is a newly comprehensive picture of the way that solar R&D in China is organized and funded. This analysis, which the report presents in both a diagram and words, draws from an extensive review of Chinese government documents, scholarly studies, and conversations with dozens of Chinese government officials,

academics, and solar-industry executives. It shows the extent to which China's solar-R&D activities depend on a relationship between the government and domestic companies far closer than the relationship that typically prevails in countries in the West.

The New Solar System also provides new details about China's spending on solar R&D, though this assessment remains limited, because China is far more opaque about its level of solar-R&D spending than are most countries active in solar research. The study clarifies the path by which the Chinese government funds its solar scientists. And it finds both that the average China-based solar manufacturer spends significantly less on R&D than does its U.S.-based counterpart—a comparison partially offset by the fact that R&D is cheaper in China than in the United States—and that Chinese solar R&D spending is rising.

China, as reflected in its latest broad economic-planning document, the Thirteenth Five-Year Plan, is intent on upgrading its solar enterprise from one that merely manufacturers and installs technology developed by others to one that also innovates and develops technology. China is systematically restructuring its government support for solar R&D in an effort to make it more effective and efficient.

Manufacturing

China dominates global solar manufacturing. In 2016, China accounted for 52% of polysilicon manufacturing capacity, 81% of silicon-solar-wafer manufacturing capacity, 59% of silicon-solar-cell manufacturing capacity, and 70% of crystalline-solar-module manufacturing capacity in the world, according to IHS Markit. The United States, by contrast, accounted for 11% of the world's polysilicon production capacity, 0.1% of wafer manufacturing capacity, 1% of cell manufacturing capacity, and 1% of module manufacturing capacity.

The New Solar System finds that Chinese solar supply chain is strong in producing materials and durable goods that require extensive labor, small to medium capital investment, and few advanced technical skills. The Chinese solar supply chain is at this point weaker in producing more technologically advanced goods but is steadily improving.

The commonly understood picture of Chinese solar production is of a global industry all but totally centralized in one country. A key conclusion of *The New Solar System* is that this picture is quickly changing. In two closely related shifts, the solar industry is consolidating in a corporate sense and decentralizing geographically. The industry is consolidating around a smaller number of players, each of which is spreading its operations—from R&D, to manufacturing, to deployment—across the globe. This is an important sign of industry maturation. It resembles transformative stages in the growth of other global manufacturing sectors, from automobiles to electronics. One result is that, more and more, the geographic footprints of leading solar companies look similar—whether those companies are based in China, in the United States, or elsewhere.

Precisely how this decentralization of the solar industry will play out—which parts of solar manufacturing will happen in which countries—is impossible to predict. But the fact that the decentralization has begun signals that countries that previously considered themselves uncompetitive as a locus for solar manufacturing now have reason to reassess that assumption. Importantly, this does not mean that every country will be globally competitive in every segment of solar manufacturing. What it does mean is that the question of national comparative advantage in the global solar industry—the question of which countries do what well—now is extraordinarily relevant and nuanced.

The New Solar System finds that Chinese solar manufacturing is maturing in four fundamental ways:

- The industry is integrating up and down the value chain—from polysilicon to wafers, cells, modules and balance-of-system components—with fewer bigger companies dominating the entire global solar enterprise.
- The industry is expanding its Chinese production capacity, but, increasingly, it is doing so by upgrading assembly lines and not only by building additional ones.
- The industry is ramping up manufacturing outside of China, in large part a response to tariffs imposed by the United States and the European Union on Chinese-produced solar goods.
- Solar-product manufacturers from outside China are entering China, though thus far on a small scale. So far, China-based solar manufacturers have not put factories of any scale in the United States.

China's solar industry is a textbook lesson in the power of manufacturing "clusters." The epicenter of the Chinese solar industry—and thus of the global solar industry—is the Yangtze River Delta, an area that includes Shanghai and parts of two provinces to its west. *The New Solar System* details the growth of the Yangtze River Delta solar-manufacturing cluster, including, notably, the role of government subsidies and of a key feature of China's manufacturing prowess: the industrial park.

Government subsidies are probably the aspect of China's solar enterprise most hotly disputed in the West. They are a chief driver of trade complaints that Western solar companies have launched against their Chinese competitors. Those complaints have led to U.S. and European tariffs—measures that sparked Chinese tariffs in response. All levels of government in China—national, provincial, and local—provide a range of subsidies to the Chinese solar industry. (And China, for its part, has complained to international trade authorities about the subsidies that the United States and European countries provide to their solar firms.) Quantifying China's solar subsidies is extraordinarily difficult, owing to a lack of transparent Chinese government data. But *The New Solar System* paints a newly detailed picture of these subsidies using a range of available information. Importantly, China now is redesigning its solar-deployment subsidies, restructuring them for more economic efficiency and learning from past policy-design mistakes both in China and in other countries that have heavily subsidized solar deployment.

Deployment

At the end of 2010, China had just 800 megawatts of solar capacity installed within its borders. By the end of 2016, Chinese officials estimate, the country had installed approximately 76,500 megawatts. To put this into perspective, China in five years added more solar capacity than Germany, previously the world's solar leader, deployed over a period of two decades.

China is widely expected to remain by far the world's largest solar-deployment market for many years to come. China's Thirteenth Five Year Plan for Solar Energy Development, issued in December 2016, calls for cumulative solar-capacity deployment in China of some 110,000 megawatts by 2020, though senior Chinese government officials believe actual deployment by then will total closer to 150,000 megawatts. That would amount to approximately half of all the solar capacity estimated to have been deployed globally as of the end of 2016.

One significant problem impeding solar deployment in China has been what is known as curtailment: the rejection by China's grid operators of a portion of the electricity that China's solar projects generate. China's solar deployment is concentrated overwhelmingly in a handful of provinces, many of them in rural areas located far from population centers that need electricity and in areas where transmission development has not kept pace with renewables deployment and there is little storage capacity. In

some of those provinces, solar-curtailment rates have approached 30%.

The Chinese government has concluded that, to deploy solar capacity at the massive levels it has targeted, China will have to get more efficient in the way it spends its solar-deployment capital. So China is moving to develop more-efficient solar-deployment tools—through government policy and through private investment mechanisms. Three aspects of this attempt to increase the efficiency of solar-deployment capital are particularly noteworthy: reform of China's "feed-in tariff," the country's main solar-deployment incentive; reform of China's solar-project approval process; and the introduction of a variety of new solar-deployment financing mechanisms.

Recommendations for U.S. Policy

Framework

The best way for any country—including the United States—to derive lasting economic gain from the growing solar industry is to help maximize the industry's efficient global growth. This framework suggests three overarching priorities for U.S. policymakers:

- **Seek above all else to reduce solar power's costs.** Solar power, despite significant cost cuts over the past decade, remains too expensive to scale to the level that would make a meaningful environmental difference, particularly when its intermittency is taken into account. In 2016, the DOE announced the solar industry had achieved 70% of cost-cut targets that the DOE had set five years before—and so it unveiled more-aggressive unsubsidized-cost targets for 2030: $0.03 per kilowatt-hour for utility-scale solar, $0.04 per kilowatt-hour for commercial rooftop solar, and $0.05 per kilowatt-hour for residential solar. Reducing the cost of solar energy to this extent would require maximizing international R&D cooperation, manufacturing in the most-cost-effective locations, and improving solar-project permitting and deployment. And it would require significant advances in two enablers—energy storage and transmission—that will be crucial to overcoming solar's intermittency and its varying availability across regions including North America.
- **Embrace the reality of a globalizing solar industry.** U.S. policy bearing on solar should reorient fundamentally so that it seeks to leverage, not defeat, China. More than ever before, the solar industries in China and the United States are intertwined: Shareholders across the globe invest in both of them, capital moves between them, many of the same companies are active in both of them, and market dynamics in one influence fortunes in the other. Key players in both countries increasingly believe that they will profit more if each country focuses on exploiting its comparative advantages in the globalizing solar industry than if it orients policy around trying to beat the other. That conclusion marks a major shift from the thinking that prevailed just five years ago, when the solar sector was more a patchwork of small and distinct national industries than the interconnected, international force it is becoming today.
- **Focus U.S. federal support for solar primarily on R&D and deployment and only secondarily on manufacturing.** Certain types of solar manufacturing in the United States seem increasingly feasible. But U.S. policymakers should regard manufacturing as a subordinate, not a primary, policy goal. Solar manufacturing is unlikely to produce large numbers of U.S. jobs, because it is an increasingly automated process. The majority of solar jobs are in areas other than manufacturing: in sales, installation, operation and maintenance, and R&D.

R&D *Recommendations*

The United States remains a leader in many aspects of solar R&D. This leadership has been backed by significant U.S.-government funding, and it will be important to solar's global growth. The United States should:

- Significantly increase U.S. spending on R&D for solar and for solar-enabling technologies such as storage and transmission, in both the public and private sectors, to help propel solar's global growth and to ensure that the United States remains a leader in it.
- Broaden international solar-R&D efforts to include China so that China's increasing solar innovation informs efforts elsewhere. For the United States, cooperating with China on solar R&D poses real and important challenges, including concerns about the protection of intellectual property and about national security. But not cooperating with China on solar R&D also presents significant risks, including reduced relevance in the silicon-based solar technologies that command the majority of today's market.
- Reform a federal policy that requires that those who accept federal R&D funding, including for solar R&D, promise to manufacture "substantially" in the United States any technologies that they develop through that R&D. According to a wide range of U.S. solar executives, scientists, and even government officials involved in implementing it, this provision is outdated and counterproductive. In its effort to maximize U.S. solar-manufacturing jobs, it risks weakening U.S. solar R&D, an activity with potentially greater long-term economic value to the United States than solar manufacturing.

Manufacturing Recommendations

U.S. solar manufacturing is rising significantly but from an extremely small base. As noted above, the United States in 2016 accounted for 0.1% of global wafer manufacturing capacity, 1% of global cell manufacturing capacity, and 1% of module manufacturing capacity. Several new or expanded U.S. solar-cell and -module factories are under construction or expected to be built over the next two years. Yet predictions are that, at least in the near term, U.S. solar manufacturing will remain small in the global context. The key opportunity for the United States is to identify those sorts of solar manufacturing that are likely to be economic absent significant government subsidy.
The New Solar System concludes that U.S. solar manufacturing is likely to prove economically viable for three categories of solar products:

- products for U.S. consumption that are expensive to import;
- export-oriented goods that the United States can competitively produce at large scale because of cheap U.S. natural gas;
- and export-oriented goods developed with U.S. R&D talent that the United States is well-positioned to manufacture in relatively small quantities in initial factories but that may shift to cheaper manufacturing locations overseas as they scale up.

Around the world, solar manufacturing, like manufacturing in many other sectors, has centered on particular geographic clusters that leverage well-developed supply chains, established transportation infrastructure, abundant low-cost energy, and often partnerships with local R&D institutions such as universities or government-affiliated labs. The United States has focused on developing two solar-manufacturing clusters: California's Bay Area and New York's upstate region near Buffalo. One way to grow the upstate New York solar cluster, in particular, would be to expand an existing solar-R&D effort there to include companies beyond U.S.-based firms.

An important element of China's buildup of its solar-manufacturing enterprise has been the financing that Chinese lenders have provided to China-based solar firms for their international expansion. The U.S. Export-Import Bank is the subject of ongoing political disagreement but has played, and could continue to play, an important role in exports by U.S.-based solar firms.

Deployment Recommendations

Certain areas of the United States—particularly the Southwest, Mountain West, and California—have some of the best solar resources on the planet. Largely in those regions, U.S. solar deployment is surging. In 2015, the United States was the third-largest deployer of solar modules in the world, behind China and Japan. It installed 7,200 megawatts of solar capacity in 2015, up 16% from 2014. Cumulatively, the United States installed 25,600 megawatts of solar capacity as of 2015, placing it fourth globally, behind China, Germany, and Japan. And in 2016, new U.S. solar deployment increased hugely to 14,600 megawatts, essentially twice the figure for 2015. Yet despite this growth, the United States still ranks 25th globally in the percentage of its electricity—just under 1%—that it generates from solar.

In scaling up solar power for itself and for the world, the United States could do much more. It should focus on two broad categories.

The first is U.S. domestic energy policy. U.S. solar deployment would benefit from:

- establishing a significant U.S. price on carbon, the single most important policy step the country could take in incentivizing private enterprise to develop and deploy technologies, such as solar, that curb climate change;
- continuing the Clean Power Plan, a federal rule finalized in 2015 that would cut greenhouse-gas emissions from U.S. power plants; though the plan is the subject of current legal challenge, and analysts differ as to how significantly it would drive solar deployment, it would help propel the shift from higher-carbon to lower-carbon electricity sources, and so, if it survives in the courts, the federal government and the states should implement it;
- achieving an equitable outcome to intensifying disputes over "net energy metering," a state-level policies that require utilities to pay consumers for electricity—generally solar power—that the consumers generate and feed into the power grid;
- supporting state renewable-portfolio standards (RPSs), which have been key drivers of solar deployment in the United States and remain important because solar power is, in most places, more expensive than conventional power;
- extending to solar energy—in the wake of a 2015 Congressional decision to phase down the federal investment tax credit (ITC) for solar—certain tax benefits enjoyed by fossil-fueled energy projects, including the master limited partnership (MLP);
- learning lessons from successes and failures of federal loans and loan guarantees provided by the DOE's Loan Programs Office (LPO);
- and ensuring that U.S. federal agencies adhere to the requirements of a 2015 law that requires them to collaborate much more than before in the way they conduct environmental reviews and permitting of a host of large-scale developments, including renewable-energy projects.

The second area ripe for U.S. federal action is to facilitate engagement by U.S. investors and financial institutions in the Chinese solar market.

Several leading U.S. solar-technology firms have sold large stakes or their entire businesses to Chinese investors. U.S. investment banks have been active in helping China-based solar firms tap the public markets for capital for manufacturing, both through initial public offerings and through

follow-on offerings. And China-based solar manufacturers are beginning to invest significant sums in developing solar projects in the United States. So far, however, neither U.S. lenders nor U.S. solar developers have been active in China's burgeoning solar-deployment market.

Now is the time for that to change. U.S. solar companies, investors, and policymakers have pioneered innovative methods of solar-deployment financing. In what may prove to be one of its most significant findings, *The New Solar System* points up rising interest among high-ranking government officials in China in deploying in China certain U.S.-developed financial structures. Those structures could facilitate both debt and equity financing in China by institutions beyond banks, whose capital tends to be expensive and which have dominated the Chinese market so far. The hope in China is that more-innovative financing methods would reduce the cost of capital, helping expand solar deployment in the largest solar market in the world.

Increasing U.S. financiers' involvement in China's solar market inevitably will raise complex issues, including questions about China's electricity-market regulations—regulations that currently make it difficult for foreign investors to participate. But the prize is substantial: China plans by 2030 to spend ¥41 trillion ($5.95 trillion) on low-carbon technologies, including solar.

The U.S. government could act as a powerful facilitator of increased involvement by U.S. investors and solar developers in the Chinese solar-deployment market. Doing so could help unleash private capital to combat carbon emissions—as study after study has concluded that private capital will be far more important than direct government spending in cleaning up the global energy system. Amid continuing animosity between Beijing and Washington on many fronts, including on the issue of solar tariffs, the possibility of increased involvement by U.S. investors in China's solar-deployment market is a significant opportunity.

Conclusion

China and the United States find themselves at an unprecedented moment in the growth of solar power. How they proceed will do much determine whether solar energy emerges as a mainstream energy source and, in the process, as an engine of significant economic growth and carbon reductions. There are many reasons to be skeptical that the world's two largest energy consumers and carbon emitters will find the will to work more closely together to scale up solar power to meaningfully address the climate challenge. Yet *The New Solar System* concludes that each of them has an even more-compelling reason to do so: economic self-interest.