Executive Summary

Solar electricity generation is one of very few low-carbon energy technologies with the potential to grow to very large scale. As a consequence, massive expansion of global solar generating capacity to multi-terawatt scale is very likely an essential component of a workable strategy to mitigate climate change risk. Recent years have seen rapid growth in installed solar generating capacity, great improvements in technology, price, and performance, and the development of creative business models that have spurred investment in residential solar systems. Nonetheless, further advances are needed to enable a dramatic increase in the solar contribution at socially acceptable costs. Achieving this role for solar energy will ultimately require that solar technologies become cost-competitive with fossil generation, appropriately penalized for carbon dioxide (CO_2) emissions, with — most likely — substantially reduced subsidies.

This study examines the current state of U.S. solar electricity generation, the several technological approaches that have been and could be followed to convert sunlight to electricity, and the market and policy environments the solar industry has faced. Our objective is to assess solar energy's current and potential competitive position and to identify changes in U.S. government policies that could more efficiently and effectively support the industry's robust, long-term growth. We focus in particular on three preeminent challenges for solar generation: reducing the cost of installed solar capacity, ensuring the availability of technologies that can support expansion to very large scale at low cost, and easing the integration of solar generation into existing electric systems. Progress on these fronts will contribute to greenhouse-gas reduction efforts, not only in the United States but also in other nations with developed electric systems. It will also help bring light and power to the more than one billion people worldwide who now live without access to electricity.

This study considers grid-connected electricity generation by photovoltaic (PV) and concentrated solar (or solar thermal) power (CSP) systems. These two technologies differ in important ways. A CSP plant is a single large-scale installation, typically with a generating capacity of 100 megawatts (MW) or more, that can be designed to store thermal energy and use it to generate power in hours with little or no sunshine. PV systems, by contrast, can be installed at many scales — from utility plants with capacity in excess of 1 MW to residential rooftop installations with capacities under 10 kilowatts (kW) — and their output responds rapidly to changes in solar radiation. In addition, PV can use all incident solar radiation while CSP uses only direct irradiance and is therefore more sensitive to the scattering effects of clouds, haze, and dust.

REALIZING SOLAR ENERGY'S TECHNICAL POTENTIAL

Photovoltaic Modules

The cost of installed PV is conventionally divided into two parts: the cost of the solar module and so-called balance-of-system (BOS) costs, which include costs for inverters, racking and installation hardware, design and installation labor, and marketing, as well as various regulatory and financing costs. PV technology choices influence both module and BOS costs. After decades of development, supported by substantial federal research and development (R&D) investments, today's leading solar PV technology, wafer-based crystalline silicon (c-Si), is technologically mature and large-scale c-Si module manufacturing capacity is in place. For these reasons, **c-Si systems likely will dominate the solar energy market for the next few decades and perhaps beyond. Moreover, if the industry can substantially reduce its reliance on silver for electrical contacts, material inputs for c-Si PV generation are available in sufficient quantity to support expansion to terawatt scale.**

However, current c-Si technologies also have inherent technical limitations — most importantly, their high processing complexity and low intrinsic light absorption (which requires a thick silicon wafer). The resulting rigidity and weight of glass-enclosed c-Si modules contribute to BOS cost. **Firms that manufacture c-Si modules and their component cells and input materials have the means and the incentive to pursue remaining opportunities to make this technology more competitive through improvements in efficiency and reductions in manufacturing cost and materials use. Thus there is not a good case for government support of R&D on current c-Si technology.**

The limitations of c-Si have led to research into thin-film PV alternatives. Commercial thin-film PV technologies, primarily cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) solar cells, constitute roughly 10% of the U.S. PV market today and are already cost-competitive with silicon. **Unfortunately, some commercial thin-film technologies are based on scarce elements, which makes it unlikely that they will be able to achieve terawatt-scale deployment at reasonable cost.** The abundance of tellurium in Earth's crust, for example, is estimated to be only one-quarter that of gold.

A number of emerging thin-film technologies that are in the research stage today use novel material systems and device structures and have the potential to provide superior performance with lower manufacturing complexity and module cost. Several of these technologies use Earth-abundant materials (even silicon in some cases). **Other properties of some new thin-film technologies, such as low weight and compatibility with installation in flexible formats, offer promise for enabling reductions in BOS costs along with lower module costs.**

Though these emerging technologies are not nearly competitive with c-Si today, they have the potential to significantly reduce the cost of PV-generated electricity in the future. And while the private sector is likely to view R&D investments in these technologies as risky, the payoff could be enormous. Therefore, **to increase the contribution of solar energy to long-term climate change mitigation, we strongly recommend that a large fraction of federal resources available for solar research and development focus on environmentally benign, emerging thin-film technologies that are based on Earth-abundant materials.** The recent shift of federal dollars for solar R&D away from fundamental research of this sort to focus on near-term cost reductions in c-Si technology should be reversed.

Concentrated Solar Power

CSP systems could be deployed on a large scale without encountering bottlenecks in materials supply. Also, the ability to include thermal energy storage in these systems means that CSP can be a source of dispatchable electricity. The best prospects for improving CSP economics are likely found in higher operating temperatures and more efficient solar energy collection. Therefore **R&D and demonstration expenditures on CSP technology should focus on advances in system design, including single-focus systems such as solar towers, and in the**

underlying materials science, that would allow for higher-temperature operations, and on the development of improved systems for collecting and receiving solar energy.

Historically, U.S. federal government support for CSP technology has included loan guarantees for commercial-scale installations. CSP plants only make economic sense at large scale and, given the technical and financial risks, investors in these large installations are naturally conservative in their selection of system designs and component technologies. Missing in federal efforts to promote CSP technology has been support for pilot-scale plants, like those common in the chemical industry, that are small enough to allow for affordable higher-risk experimentation, but large enough to shed light on problems likely to be encountered at commercial scale. Therefore **we recommend that the U.S. Department of Energy establish a program to support pilot-scale CSP systems in order to accelerate progress toward new CSP system designs and materials.**

THE PATH TO COST COMPETITIVENESS

PV Deployment

As of the end of 2014, PV systems accounted for over 90% of installed U.S. solar capacity, with about half of this capacity in utility-scale plants and the balance spread between residential and commercial installations. The industry has changed rapidly. In the past half-dozen years, U.S. PV capacity has expanded from less than 1,000 MW to more than 18,000 MW. Recent growth has been aided in part by a 50%–70% drop in reported PV prices (without federal subsidies) per installed peak watt. (The peak watt rating of a PV module or system reflects its output under standard test conditions of irradiance and temperature.) Almost all of this improvement has reflected falling prices for modules and inverters. In addition, the market structure for solar energy is changing, particularly at the residential level, with the evolution of new business models, the introduction of new financing mechanisms, and impending reductions in federal subsidies.

Currently, the estimated installed cost per peak watt for a residential PV system is approximately 80% greater than that for a utility-scale plant, with costs for a typical commercial-scale installation falling somewhere in between. Module costs do not differ significantly across sectors, so the major driver of cost differences in different market segments is in the BOS component, which accounts for 65% of estimated costs for utility-scale PV systems, but 85% of installed cost for residential units. Experience in Germany suggests that several components of BOS cost, such as the cost of customer acquisition and installation labor, should come down as the market matures. Costs associated with permitting, interconnection, and inspection (PII) may be more difficult to control: across the United States, thousands of municipal and state authorities and 3,200 organizations that distribute electricity to retail customers are involved in setting and enforcing PII requirements. **A national or regional effort to establish common rules and procedures for permitting, interconnection, and inspection could help lower the PII component of installed system cost, particularly in the residential sector and perhaps in commercial installations as well.**

In the past few years, the nature of the residential solar business in the United States has changed appreciably. A third-party ownership model, which is currently allowed in half the states, is displacing direct sales of residential PV systems by enabling homeowners to avoid up-front capital costs. **The development of the third-party ownership model has been a boon to residential PV development in the United States, and residential solar would expand more rapidly if third-party ownership were allowed in more states.**

Today the estimated cost for a utility-scale PV installation closely matches the average reported price per peak watt, indicating active competition in the utility segment of the PV market. However, **a large difference exists between contemporary reported prices and estimated costs for residential PV systems, indicating that competition is less intense in this market segment.**

Two influences on PV pricing are peculiar to the U.S. residential market and to the third-party ownership model. One is the effect of current federal tax subsidies for solar generation: a 30% investment tax credit (ITC) and accelerated depreciation for solar assets under the Modified Accelerated Cost Recovery System (MACRS). Third-party owners of PV systems generally need to operate on a large scale to realize the value of these provisions, which creates a barrier to entry. In addition, because there is generally little price competition between third-party installers, PV developers often are not competing with one another to gain residential customers, but with the rates charged by the local electric distribution company.

Some of the largest third-party solar providers operate as vertically integrated businesses, and their systems are not bought and sold in "arm's-length" transactions. Instead, for purposes of calculating federal subsidies they typically can choose to estimate their units' fair market value based on the total income these units will yield. **In a less than fully competitive market, this estimation approach can result in fair market values that exceed system costs and thus lead to higher federal subsidies than under a direct sale model. Where competition is not intense, subsidies are not necessarily passed on to the residential customer.**

Over time, more intense competition in the residential PV market (as a natural consequence of market growth and the entry of additional suppliers) should direct more of the available subsidy to the residential customer by driving down both power purchase rates under third-party contracts and prices in direct sales. And these pressures will also intensify industry efforts to reduce the BOS component of installation cost.

Even with greater competition, however, an inherent inefficiency in the current, investment-based federal subsidy system will remain. Because residential solar has a higher investment cost per peak watt, and because the magnitude of the federal subsidy is based on a provider-generated calculation of fair market value, residential solar receives far higher subsidies per watt of deployed capacity than utility-scale solar. Moreover, because third-party contracts are influenced by local utility rates, which vary considerably across the country, the per-watt subsidy for identical residential or commercial installations can differ substantially from region to region.

Solar Economics

The economic competitiveness of solar electricity relative to other generation technologies depends on its cost and on the value of its output in the particular power market in which it is sold. A commonly used measure for comparing different power sources is the levelized cost of electricity (LCOE). However, **LCOE is an inadequate measure for assessing the competitiveness of PV, or for comparing PV with CSP or conventional generation sources, because the value per kilowatt-hour (kWh) of PV generation depends on many features of the regional electricity market, including the level of PV penetration.** The more PV capacity is online in a given market, for instance, the less valuable is an increment of PV generation.

Utility-Scale Solar

Estimates of LCOE are nonetheless useful because they give a rough impression of the competitive position of solar at its current low level of penetration in the U.S. electricity supply mix. In assessing the economics of utility-scale solar generation, the appropriate point of comparison is with other utility-scale generating technologies, such as natural gas combined cycle (NGCC) plants. **Without a price on CO_2 emissions and without federal subsidies, current utility-scale PV electricity has a higher LCOE than NGCC generation in most U.S. regions, including in relatively sunny southern California.**

Because of the structure of current federal subsidies, a significant fraction of their value is consumed by the costs of accessing the tax equity market, since most developers lack sufficient profits to take full advantage of the ITC and MACRS on their own. **If, however, the ITC and MACRS were 100% effective (i.e., if solar generators could capture the full value of these subsidies without incurring any costs of accessing the tax equity market), utility-scale PV would be cost competitive on an LCOE basis with NGCC in California, though not in Massachusetts.** By creating other cash flows for current utility solar projects, state and local support policies have facilitated the spread of utility-scale PV to many U.S. regions where it would not otherwise be economic.

Designing CSP plants with thermal energy storage lowers LCOE and allows them to generate electricity during periods when it is most valuable, making them more competitive with other generation sources. Nevertheless, **utility-scale PV generation is around 25% cheaper than CSP generation, even in a region like southern California that has strong direct insolation. Utility-scale PV is about 50% cheaper than CSP in a cloudy or hazy region like Massachusetts. Even with 100% effective federal subsidies, CSP is not competitive with NGCC generation today.**

Residential Solar

If solar generation is valued for its contribution at the system or wholesale level, and assuming that solar penetration causes no net increase in distribution costs (see below), **PV generation by residential systems is, on average, about 70% more costly than from utility-scale PV plants. Even in California, and even including 100% effective federal subsidies, residential PV is not competitive with NGCC generation on an LCOE basis.** The economics of commercial-scale PV installations fall between the polar cases of utility- and residential-scale installations. Lowering BOS costs to the levels more typical of PV installations in Germany would bring residential PV closer to a competitive position, but residential PV would still be more expensive than utility-scale PV or NGCC generation.

In most U.S. electricity distribution systems, generation by grid-connected residential PV systems is compensated under an arrangement known as net metering. In this regime, the owner of the residential PV installation pays the retail residential rate for electricity purchased from the local distribution utility and is compensated at this same rate for any surplus PV output fed back into the utility's network. Under these conditions, the commonly used investment criterion is *grid parity*, which is achieved when it is just as attractive to employ a rooftop PV system to meet part of the residential customer's electricity needs as it is to rely entirely on the local distribution company. The highest incremental retail electricity rates in California are well above the estimated LCOE of residential PV systems in southern California, even without accounting for federal subsidies. And **with the current combination**

of federal, state, and local subsidies, the price of residential PV has now fallen below the level needed to achieve grid parity in many jurisdictions that apply net metering.

INTEGRATION INTO EXISTING ELECTRIC SYSTEMS

Distributed Solar

Introducing distributed PV has two effects on distribution system costs. In general, line losses initially decrease as the penetration of distributed PV increases. However, **when distributed PV grows to account for a significant share of overall generation, its net effect is to increase distribution costs (and thus local rates). This is because new investments are required to maintain power quality when power also flows from customers back to the network, which current networks were not designed to handle.** Electricity storage is a currently expensive alternative to network reinforcements or upgrades to handle increased distributed PV power flows.

In an efficient and equitable distribution system, each customer would pay a share of distribution network costs that reflected his or her responsibility for causing those costs. Instead, most U.S. utilities bundle distribution network costs, electricity costs, and other costs and then charge a uniform per-kWh rate that just covers all these costs. **When this rate structure is combined with net metering, which compensates residential PV generators at the retail rate for the electricity they generate, the result is a subsidy to residential and other distributed solar generators that is paid by other customers on the network.** This cost shifting has already produced political conflicts in some cities and states — conflicts that can be expected to intensify as residential solar penetration increases.

Because of these conflicts, robust, long-term growth in distributed solar generation likely will require the development of pricing systems that are widely viewed as fair and that lead to efficient network investment. Therefore, **research is needed to design pricing systems that more effectively allocate network costs to the entities that cause them.**

Wholesale Markets

CSP generation, when accompanied by substantial thermal energy storage, can be dispatched in power markets in a manner similar to conventional thermal or nuclear generation. Challenges arise, however, when PV generators are a substantial presence in wholesale power markets. In about two-thirds of the United States, and in many other countries, generators bid the electricity they produce into competitive wholesale markets. PV units bid in at their marginal cost of production, which is zero, and receive the marginal system price each hour. **In wholesale electricity markets, PV displaces those conventional generators with the highest variable costs. This has the effect of reducing variable generation costs and thus market prices. And, since the generation displaced is generally by fossil units, it also has the effect of reducing CO_2 emissions.**

This cost-reducing effect of increased PV generation, however, is partly counterbalanced by an increased need to cycle existing thermal plants as PV output varies, reducing their efficiency and increasing wear and tear. The cost impact of this secondary effect depends on the existing generation mix: it is less acute if the system includes sufficient gas-fired combustion turbines or other units with the flexibility to accommodate the "ramping" required by fluctuations in solar output. At high levels of solar penetration, it may even be necessary to curtail production from solar facilities to reduce cycling of thermal power plants. Thus, **regulations that mandate the dispatch of solar generation, or a large build-out of distributed PV capacity that cannot be curtailed, can lead to increased system operating costs and even to problems with maintaining system reliability.**

In the long term, as the non-solar generation mix adjusts to substantial solar penetration with the installation of more flexible peaking capacity, the economic value of PV output can be expected to rise. Also, **net load peaks can be reduced — and corresponding cycling requirements on thermal generators can be limited — by coordinating solar generation with hydroelectric output, pumped storage, other available forms of energy storage, and techniques of demand management. Because of the potential importance of energy storage in facilitating high levels of solar penetration, large-scale storage technologies are an attractive focus for federal R&D spending.**

Whatever the structure of other generation assets in a power system, the penetration of PV on a commercial basis will be self-limiting in deregulated wholesale markets. At low levels of solar penetration, marginal prices for electricity on most systems tend to be higher in the daytime hours, when PV generation is available, than at night. As solar generation during the day increases, however, marginal prices during these peak-demand hours will fall, reducing the return to solar generators. **Even if solar PV generation becomes cost-competitive at low levels of penetration, revenues per kW of installed capacity will decline as solar penetration increases until a breakeven point is reached, beyond which further investment in solar PV would be unprofitable.** Thus significant cost reductions may be required to make PV competitive at the very substantial penetration levels envisioned in many low-CO_2 scenarios.

In systems with many hours of storage, such as systems that include hydroelectric plants with large reservoirs, this effect of solar penetration is alleviated. Since opportunities for new hydroelectric generation or pumped storage are limited, **the self-limiting aspect of solar generation — wherein high levels of penetration reduce solar's competitiveness — further highlights the importance of developing economical multi-hour energy storage technologies as part of a broader strategy for achieving economical large-scale PV deployment.**

DEPLOYMENT OF CURRENT TECHNOLOGY

The motivations often cited to support subsidizing deployment of current solar technology range from short-term emissions reductions to job creation. In our view, however, the dominant objective should be to create the foundation for large-scale, long-term growth in solar electricity generation as a way to achieve dramatic reductions in future CO_2 emissions while meeting growing global energy demand, and secondarily to achieve this objective with the most effective use of public budgets and private resources. The least-cost way to promote solar deployment would be via one of several price-based policies that reward the output of solar generation according to its value to the electricity supply system. In the United States, however, the primary federal-level incentive for solar energy is a subsidy to investment in solar facilities, using a costly method — tax credits — to provide it. In addition, many U.S. cities and states subsidize investments in solar electricity generation through various grants, low-interest loans, and tax credits.

Subsidies for solar technologies would be much more effective per taxpayer dollar spent if they rewarded generation, not investment. This change would correct the inefficiency in the current federal program, under which a kWh generated by a residential PV system gets a much higher subsidy than a kWh generated by a nearby utility-scale plant and facilities receive higher subsidies per kWh, all else equal, the less insolation they receive.

At the time of this writing, the main federal solar subsidy — the investment tax credit — is scheduled to fall sharply at the end of 2016, with no plans for a replacement. Congress should reconsider this plan. Current policies have spurred increases in market scale, customer familiarity, and competition that are contributing to the solar industry's long-term prospects. **Particularly in the absence of a charge on CO_2 emissions, now is the wrong time to drastically reduce federal financial support for solar technology deployment. The federal investment tax credit should not be restored to its current level, but it should be replaced with an output-based subsidy.**

If Congress nonetheless restores an investment subsidy, **it should replace tax credits with direct grants, which are both more transparent and more effective.** Finally, if tax-based incentives are to be used to spur solar deployment, **the investment tax credit should be replaced with an instrument that avoids dependence on the tax equity market, such as master limited partnerships.**

Reforming some of the many mandates and subsidies adopted by state and local governments could also yield greater results for the resources devoted to promoting solar energy. In particular, **state renewable portfolio standard (RPS) requirements should be replaced by a uniform nationwide program. Until such a nationwide program is in place, state RPS policies should not restrict the siting of eligible solar generators to a particular state or region.**

A CLOSING THOUGHT

In the face of the global warming challenge, solar energy holds massive potential for meeting humanity's energy needs over the long term while cutting greenhouse gas emissions. Solar energy has recently become a rapidly growing source of electricity worldwide, its advancement aided by federal, state, and local policies in the United States as well as by government support in Europe, China, and elsewhere. As a result the solar industry has become global in important respects.

Nevertheless, while costs have declined substantially in recent years and market penetration has grown, major scale-up in the decades ahead will depend on the solar industry's ability to overcome several major hurdles with respect to cost, the availability of technology and materials to support very large-scale expansion, and successful integration at large scale into existing electric systems. Without government policies to help overcome these challenges, it is likely that solar energy will continue to supply only a small percentage of world electricity needs and that the cost of reducing carbon emissions will be higher than it could be.

A policy of pricing CO_2 emissions will reduce those emissions at least cost. But until Congress is willing to adopt a serious carbon pricing regime, the risks and challenges posed by global climate change, combined with solar energy's potential to play a major role in managing those risks and challenges, create a powerful rationale for sustaining and refining government efforts to support solar energy technology using the most efficient available policies.