Section I

Chapter 1 – Introduction and Overview

This study is one in a series of Future of studies produced by the MIT Energy Initiative that aim to provide useful references for decision-makers and balanced, fact-based recommendations to improve public policy, particularly in the United States. Earlier studies in this series have considered the futures of nuclear power, coal, natural gas, and the electric grid — all major features in today’s energy landscape.

By comparison, solar energy is currently much less important. It accounts for only around 1% of global electricity generation and a smaller fraction of U.S. generation. It nonetheless deserves serious attention today because solar energy may be called upon to play a much larger role in the global energy system by mid-century and because removing several important obstacles over the next several decades will greatly increase the likelihood that solar energy will be able to answer that call. Our aim in this study is to help decision-makers understand solar energy’s potential future importance, the obstacles that may prevent solar technologies from realizing that potential, and the elements of sound public policies that could reduce current obstacles.

Solar energy’s importance ultimately derives from the profound long-term threat posed by global climate change. Carbon dioxide (CO$_2$) emissions from the combustion of fossil fuels account for by far the largest share of greenhouse gases that are causing climate change. Because CO$_2$ remains in the atmosphere for centuries, slowing the increase in the atmospheric concentration of CO$_2$ requires reducing global CO$_2$ emissions, which have been rising at an accelerating rate since the industrial revolution.

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Solar energy has the potential to play a major role in achieving this goal. About two-thirds of CO$_2$ emissions from fossil fuels are associated with electricity generation, heating, and transportation. We already know how to use solar energy to generate electricity with very low CO$_2$ emissions, and we know how to use electricity to provide heat and surface transportation services. Moreover, as we discuss further below, the solar resource is enormous, dwarfing both global energy consumption and the potential scales of other renewable energy sources. A plausible way to reduce global CO$_2$ emissions from the combustion of fossil fuels account for by far the largest share of greenhouse gases that are causing climate change. Because CO$_2$ remains in the atmosphere for centuries, slowing the increase in the atmospheric concentration of CO$_2$ requires reducing global CO$_2$ emissions, which have been rising at an accelerating rate since the industrial revolution.

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emissions despite growth in energy consumption would be to increase dramatically the use of solar energy to generate electricity and to rely more on electricity for heating and transportation.

The International Energy Agency (IEA) recently modeled several scenarios in which, as part of a worldwide response to the risks of climate change, global energy-related CO₂ emissions are cut to less than half of 2011 levels by 2050. IEA assumed that emissions reductions would be implemented at least cost, but in perhaps the most interesting scenario, growth of nuclear power is constrained by non-economic factors. In that scenario, global demand for electricity rises by 79% between 2011 and 2050, and wind, hydro, and solar supply 66% of global generation in 2050, with solar alone supplying 27%. If expansion of hydroelectric facilities were to be limited for environmental reasons, as is already the case in the United States and many other nations, solar energy would need to play an even greater role in global electricity supply to enable significant CO₂ reductions.

The chapters that follow discuss in more detail three potential obstacles that could stand in the way of solar energy’s playing a leading role in the future: cost, scaling, and intermittency. First, while the cost of solar electricity has declined dramatically in recent years and can be expected to decline further in the future, using solar energy to generate electricity is still more expensive, in many locations, than using available fossil-fueled technologies. As we note below, it has been argued that at least some of the recent cost reductions are not sustainable. On the other hand, solar energy is at an artificial cost disadvantage because the users of fossil energy pay nothing for the damages caused by the emissions they produce. Accordingly, we favor putting a price on those emissions, either directly through a carbon tax or indirectly through a cap-and-trade regime. Such a comprehensive, market-based policy would provide economy-wide incentives to reduce CO₂ emissions at the lowest possible cost.

When the penetration of solar energy increases, however, the average value of solar electricity declines because market prices are depressed during the sunny hours when solar generation is greatest. This means that even where solar generation is competitive with fossil generation today, its cost will have to fall significantly for it to remain competitive at higher levels of penetration. Thus, unless the recent cost-reduction trajectory can be continued, it is difficult to imagine that the expense of switching from fossil fuels to solar energy at very large scale would be voluntarily borne by U.S. voters, let alone by the citizens of India, China, and other developing nations. And developing nations are driving the ongoing increase in global CO₂ emissions.

Second, if solar energy is to become a leading source of electricity by mid-century, the solar industry and its supply chain must scale up dramatically. In the IEA scenario discussed above, for instance, solar electricity generation increases to more than 50 times its 2013 level by 2050. Some solar technologies in development and limited deployment rely on scarce materials; for such technologies, a scale-up of this magnitude is likely to be uneconomic. Fortunately, materials constraints do not

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viThe use of carbon capture and sequestration was also constrained, but that constraint had less impact.

viiBetween 1979 and 2011, U.S. generating capacity increased by 86%, but hydroelectric capacity declined by 4.7%.

viiiSee, for instance, Greenstone and Looney

ixFor a detailed comparison of market-based policies with some regulatory alternatives, see Rausch and Karplus.

xAccording to the IEA, solar energy only accounted for 0.3% of global electricity generation in 2011, and 2050 solar generation in the scenario discussed above was about 164 times that level. The estimate in the text is derived from these numbers, taking solar electricity as about 0.9% of total generation in 2013, per Footnote i, and noting that global generation in 2013 was about 4.7% above its 2011 level.
appear to be an issue for other emerging solar technologies or for the silicon-based technology that dominates the industry today.

Third, solar power at any location is intermittent: it varies over time in ways that are imperfectly predictable. This characteristic is a major obstacle to the large-scale use of solar generation in many regions. Today’s electric power systems must match generation with demand almost instantaneously. Since demand fluctuations are also imperfectly predictable, adding small amounts of solar generation creates no appreciable problems. But in a power system that is heavily dependent on solar energy, the intermittency of the solar resource will make the net load (the load that must be satisfied by nuclear, hydro, and fossil-fueled generation) more variable and less predictable. At levels of penetration well below those envisioned in the IEA scenario discussed above, most systems may be able to handle this increased variability by moving to more flexible fossil-fueled generators, by making demand more responsive to system conditions, and by making modest use of energy storage. In most systems, however, higher levels of solar penetration will likely require the development of economical large-scale energy storage technologies.

**SCOPE AND FOCUS OF THIS STUDY**

This study considers only the two widely recognized classes of technologies for converting solar energy into electricity — photovoltaics (PV) and concentrated solar power (CSP), sometimes called solar thermal — in their current and plausible future forms. Because energy supply facilities typically last several decades, technologies in these classes will dominate solar-powered generation between now and 2050, and we do not attempt to look beyond that date. In contrast to some earlier studies, we also present no forecasts — for two reasons. First, expanding the solar industry dramatically from its relatively tiny current scale may produce changes we do not pretend to be able to foresee today. Second, we recognize that future solar deployment will depend heavily on uncertain future market conditions and public policies — including but not limited to policies aimed at mitigating global climate change.

As in other studies in this series, our primary aim is to inform decision-makers in the developed world, particularly the United States. We concentrate on the use of grid-connected solar-powered generators to replace conventional sources of electricity. For the more than one billion people in the developing world who lack access to a reliable electric grid, the cost of small-scale PV generation is often outweighed by the very high value of access to electricity for lighting and charging mobile telephone and radio batteries. In addition, in some developing nations it may be economic to use solar generation to reduce reliance on imported oil, particularly if that oil must be moved by truck to remote generator sites. A companion working paper discusses both these valuable roles for solar energy in the developing world.

**Future solar deployment will depend heavily on uncertain future market conditions and public policies — including but not limited to policies aimed at mitigating global climate change.**
Two other uses of solar energy not discussed in our text deserve mention. First, a companion paper discusses the use of solar energy to heat water directly. This mature technology is widely deployed in areas with a favorable mix of high insolation, high prices for natural gas and electricity, and significant subsidies. Second, several approaches have been proposed to use solar energy to produce storable fuels without first generating electricity. A technology that could do this at an acceptable cost might be a valuable tool for reducing CO$_2$ emissions from transportation and, perhaps, from other sectors that presently depend on fossil fuels. Solar-to-fuels technologies could potentially also provide long-term, grid-scale energy storage for electricity generation. Unfortunately, no such technology is close to commercialization.

The next section provides a brief discussion of the solar resource, which is further discussed in Appendix A. Subsequent sections provide an overview of the remainder of this study.

**The solar resource is massive by any standard.**

**THE SOLAR RESOURCE: SCALE & CHARACTERISTICS**

As noted above, the solar resource is massive by any standard. Using current PV technology, solar plants covering only about 0.4% of the land area of the continental United States and experiencing average U.S. insolation over the course of a year could produce all the electricity the nation currently consumes. This is roughly half of the land area currently devoted to producing corn for ethanol, which contributes just under 7% of the energy content of U.S. gasoline, or about 4% of the combined areas of the Corn Belt states of Iowa, Illinois, Minnesota, Indiana, and Nebraska. Since some places in the continental United States receive as much as 80% more solar energy than others, much less land area would be required if generation sites were carefully chosen — although siting in only the sunniest locations would likely also increase the need for long-distance transmission.

At the global scale, the solar resource is broadly distributed. Where there are people, there is sunlight. Figure 1.1a shows a map of average solar intensity across the globe. Figures 1.1b–g display histograms of land area, population, and average insolation as functions of latitude and longitude. It is notable that insolation varies by no more than a factor of three among densely populated areas. Neither fossil fuel resources nor good sites for wind or hydroelectric generation are as broadly distributed.

Figure 1.1h shows average insolation and GDP per capita for the year 2011 in each country for which these data are available. Average insolation varies across a much smaller percentage range than GDP per capita, and the weak negative correlation between these two variables, as indicated by the figure, implies that poorer nations are generally not disadvantaged in their access to the solar resource.

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xiv Support for these assertions and more information on the solar resource in Appendix A.
The massive scale of the solar resource and its broad distribution globally are consistent with solar energy becoming an important source, perhaps the leading source, of electricity generation worldwide. This study is motivated by the enormous potential of solar energy as a tool to reduce global CO₂ emissions and the great importance of effecting those reductions.

Within many countries and regions, the sunniest areas do not have the highest demand for electricity. In the United States, for instance, the desert Southwest is a great location for solar electricity generation but it is relatively sparsely populated. By contrast, the Northeast has a high demand for electricity per square mile but relatively less insolation. Within the EU, there is considerably more sunlight in the south than in the north, but not more demand for electricity. Such geographical mismatches between sunlight and electricity demand create trade-offs in siting decisions: using sunny locations remote from major loads to reduce generation costs will require building long transmission lines to connect generation to those loads. Long transmission lines are expensive and, in many parts of the world, very difficult to site because of public objections.xv

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Note: Figure 1.1a shows a global map of solar irradiance averaged from 1990 to 2004 adapted from Albuisson, Lefevre, and Wald. Figure A.11b–g shows histograms of world land area [m²/°] (b), population [persons/°] (reproduced from Rankin26) (c), and average irradiance at the earth’s surface [W/m²] (d) as a function of longitude, and as a function of latitude (e–g). In (b) and (e), land area is shown in black and water area is shown in blue. Figure 1.1h shows the relationship between average insolation and GDP per capita for nations across the world for the year 2011. Each dot represents one nation.
The difficulties of integrating large-scale solar generation into electric power systems derive from a fundamental characteristic of the solar resource: its intermittency.

As noted above, the difficulties of integrating large-scale solar generation into electric power systems derive from a fundamental characteristic of the solar resource: its intermittency. That is, the solar energy received in any particular place varies over time, and some of that variation — the part not associated with time of day and season of the year — cannot be perfectly predicted.

To illustrate the intermittency of the solar resource, Figure 1.2 displays the minute-to-minute solar intensity measured at the U.S. National Renewable Energy Laboratory (NREL) in Golden, Colorado, over the entire year 2012 (including night-time hours). Numerous patterns are visible that would be present at any location in any year. The most obvious pattern is the perfectly predictable diurnal variation: the sun is on average brightest at midday and never shines at night. There is also a predictable northern hemispheric seasonal pattern. Following a particular day of the month downward through the chart, peak and total daily solar energy increase on average moving into the summer, after which they decrease moving into the winter.

In a power system that is highly reliant on solar energy, it follows from Figure 1.2 that the ability to store energy economically for several hours to meet night-time demand for electricity would be valuable, as would the ability to store energy at moderate cost from summer to winter. CSP facilities can often economically store heat for several hours and use it to generate electricity in later periods with little or no sunshine. But, as we note below and as Chapter 5 illustrates, CSP is much more expensive than PV in many locations.

Longer-term energy storage presents an even greater challenge. As discussed in Appendix C, batteries that could provide economical, large-scale electricity storage are currently unavailable for widespread deployment and may not be available in the near future.

Figure 1.2 Complete Solar Irradiance Profile in Golden, Colorado for the Year 2012

The time axis is to scale (nights are included).

xviHydroelectric facilities that involve reservoirs (as opposed to so-called run-of-the-river hydro plants) as well as pumped storage plants (in which water is pumped uphill to a reservoir, from which it is later allowed to flow downhill through a turbine to generate electricity) already provide some large-scale storage that could be utilized seasonally. But suitable sites for such facilities are quite limited in most regions.

xviiSee also Cook, Dogutan, Reece, et al.
An alternative approach to large-scale, long-term storage involves using solar or other electricity to split water into hydrogen and oxygen via electrolysis when electricity is not valuable, and then using the hydrogen to generate electricity when electricity is more valuable. While about 5% of hydrogen is currently produced by electrolysis, this approach to energy storage is not yet economical.\(^{xviii}\) It is worth noting that an alternative to seasonal storage in a power system with very heavy reliance on solar energy would be to build sufficient solar capacity to meet wintertime demand, recognizing that it would likely be necessary to curtail some solar generation during other seasons.

Figure 1.2 also shows that within and between days, rapid and relatively unpredictable variations in irradiance can arise from shifting cloud cover. On September 1, for example, solar intensity dropped by a factor of four from 12:28 pm to 12:30 pm as a result of passing clouds. The month of July is characterized by sharp afternoon reductions in solar intensity caused by the frequent afternoon thunderstorms that occur in the vicinity of Golden, Colorado. Strong day-to-day variations are also visible. For example, the integrated 24-hour insolation values for the first and second days of April differ by a factor of 15, and some overcast weather systems, as seen from the 4th to the 6th of October, persist for several days.

In PV facilities, power output responds quickly to changes in irradiance, so these rapid variations may cause problems for power systems with high levels of PV penetration (that is, at penetration levels well above those in the United States today).\(^{xix}\) As illustrated in Appendix A, when grid-connected PV facilities are dispersed spatially, their total output is less affected by cloud-related variations. Exploiting this effect may require construction of new transmission facilities, of course. Large-scale energy storage could, when available, enhance the ability of power systems to deal with relatively short-term fluctuations in solar irradiance. Supply intermittency could also be addressed by making demand more responsive to system conditions (most naturally via prices that reflect those conditions), by curtailing solar generation when its output is excessive, and by adding more conventional generation that can vary output rapidly.\(^{xx}\)

**SOLAR TECHNOLOGIES**

Chapters 2 and 3 describe the two solar technology pathways that are the focus of this study: PV and CSP. At the end of 2013, more than 97% of global solar generation capacity was PV, and less than 3% was CSP.\(^{xvi,xxi}\)
The first modern solar cells were produced in 1954 and deployed in 1958 on a U.S. satellite.

PV technology is discussed in detail in Chapter 2. The first modern solar cells were produced in 1954 and deployed in 1958 on a U.S. satellite. Those early cells relied on the silicon-wafer-based approach that continues to dominate the industry today. Manufacturing techniques have progressed enormously since then, and the price of solar cells and modules (which consist of multiple connected solar cells) has fallen dramatically. As Figure 1.3 suggests, PV generators have no moving parts: when sunlight strikes a solar cell connected to an external circuit, a direct electric current (dc) flows. PV generating facilities include solar modules and inverters that convert direct current into grid-compatible alternating current (ac), as well as other electrical and structural components, such as wires and brackets. One key advantage of solar PV over conventional fossil-fueled or nuclear generation is its modularity: solar-to-electric power conversion efficiency is unaffected by scale, though cost per unit of generating capacity is significantly lower for utility-scale installations (which generally have capacities measured in megawatts) than for residential systems (which typically have capacities measured in kilowatts).

While most PV cells made today are based on crystalline silicon, active research is underway to explore alternative designs and materials capable of reaching cost targets that are much more favorable than those anticipated for existing commercial technologies. In Chapter 2, we provide a classification scheme for new and existing PV technologies based on the complexity of their primary light-absorbing material. We further identify three characteristics that will almost certainly be shared by successful future PV technologies: higher efficiency, lower materials use, and improved manufacturability.

CSP technology, discussed in detail in Chapter 3, is much less widely deployed, even though the first CSP power station was built in Egypt in 1912–13 to run an irrigation system. Figure 1.4 shows the two CSP designs that have

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**Figure 1.3 Solar PV**

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In addition to silicon-based solar cells, cells based on thin-film technologies are now commercially deployed. However, as we discuss below, it is unlikely that these commercial thin-film technologies can make a significant contribution to global electricity generation in the future because of materials scaling considerations.
been deployed at commercial scale to date. In the older parabolic trough design, mirrors focus solar radiation on a pipe through which a fluid such as oil or a molten salt is pumped. The heated fluid is then used to produce steam that drives a turbine connected to a generator. In the power-tower design, a field of mirrors focuses solar radiation on the top of a tower through which a fluid is pumped. Power-tower plants can operate at a higher fluid temperature than parabolic trough plants, which increases overall efficiency. In either design, the output of the generator at any point in time depends on the temperature of the fluid, which is relatively insensitive to short-term changes in solar irradiance.

As a practical matter, these two CSP technologies can only be used at large scale. In addition, because CSP systems can only use direct sunlight, not sunlight diffused by haze or cloud cover, their performance is more sensitive to cloudiness and haze than the performance of PV systems. On the other hand, CSP facilities can economically provide hours of (thermal) energy storage, thereby producing power in hours with little or no sunlight, and they can be economically designed to use natural gas to supplement solar energy in a fully dispatchable hybrid configuration. Research on CSP is exploring ways to increase efficiency by attaining higher temperatures and by converting more of the incident solar energy into thermal energy.

**BUSINESS MODELS & ECONOMICS**

Chapters 4 and 5 of this study consider the factors that determine the cost and value of solar electricity. Chapter 4 discusses the determinants of capital costs for PV generating facilities and describes the business models being used to support PV installations in the United States, while Chapter 5 explores how facility capital costs, insolation, and other factors affect the cost of electricity generated by PV and CSP systems. We then go on to consider the value of solar electricity and its determinants.

PV modules are commodity products; current production is concentrated in China and Taiwan but is supported by a global supply chain. Inverters are also a commodity product, traded internationally. PV system prices at all scales have declined considerably in recent years mainly because of reductions in module and inverter prices. As Chapter 4 notes, there is
considerable debate, which we do not attempt to resolve, about the drivers behind this decline, and specifically about the importance of manufacturing improvements relative to Chinese government subsidies and excess capacity in the Chinese solar module industry. To the extent that the latter two factors are important, some of the recent declines in module prices may not be sustainable.

Modules and inverters now account for less than a third of residential PV system costs and about half of the costs of utility-scale systems in the United States. Remaining costs have not declined substantially in recent years. They include the costs of wires, brackets, and other components; the cost of labor for facility installation and other functions; the cost of financing initial installations; and installer overhead costs and profits. (PV system costs other than module costs are generally called balance-of-system or BOS costs.) In the United States, utility-scale costs and overall prices are already constrained by intense supplier competition, but competition is much less intense in the residential marketplace. Chapter 4 shows that even though module and inverter costs are essentially identical in the United States and Germany, total U.S. residential system costs are substantially above those in Germany. We discuss possible explanations and some policy implications.

Chapter 4 describes variants of the third-party ownership model, in which a homeowner buys the electricity generated on her roof from the owner of the PV system. This business model removes the need for the homeowner to make an up-front investment. Coupled with net metering, which compensates residential PV generation at the retail price of electricity and thus at a level that is generally well above the utility’s marginal cost, and a variety of subsidies that also favor residential over utility-scale installations, the third-party ownership model has fueled rapid expansion of residential PV generation in the United States. As Chapter 4 discusses, however, the residential market is still immature, and consumers often lack information. The result seems to have been a focus on competition between PV and grid-supplied electricity at retail prices, not competition between vendors of PV-generated electricity.

Chapter 5 models the economics of PV and CSP generation using today’s technologies in two U.S. locations (southern California and central Massachusetts). At the utility scale, in both locations the levelized cost of electricity (LCOE) from a CSP plant is higher than the LCOE from a PV plant, and levelized costs for both solar technologies are considerably higher than those of conventional fossil-fueled generators. These results are broadly consistent with
many other studies. The U.S. Energy Information Administration (EIA), for instance, recently published the LCOE estimates shown in Table 1.1 for new utility-scale generating plants coming on line in the United States in 2019. The maximum and minimum values shown in the table reflect regional differences in delivered fuel prices and more substantial differences in available solar and wind energy. While a good deal of uncertainty necessarily attaches to these estimates, and while the EIA’s estimates of solar costs have tended to be above those available from some other sources, it is notable that the minimum costs for solar PV and CSP in Table 1.1 are above the maximum costs for natural gas combined cycle plants and even onshore wind generators.

Chapter 5 also finds that levelized costs for residential PV are higher than for utility-scale PV because of much higher residential BOS costs in the United States. In all cases analyzed for this study, the per-kWh costs of residential generation were just over 170% of estimated costs for utility-scale generation. The fact that residential PV generation is nonetheless growing rapidly reflects, to a significant extent, the much higher per-kWh subsidies it receives.

While we follow standard practice and use LCOE as a summary measure of cost, it is important to recognize that this measure is of limited value when applied to intermittent technologies like solar for which the timing of power output is not fully controllable. Because electricity tends to be more valuable (as measured by the spot price in organized wholesale electricity markets) during the day than at night, for instance, solar electricity is more valuable on average at current prices than electricity from a baseload nuclear plant that produces at a constant rate. Thus LCOE comparisons, which do not take spot price patterns into account, tend to under-value incremental solar electricity today. But current prices reflect very low levels of solar penetration. As Chapter 8 demonstrates, once the fraction of electricity generated from solar energy rises well above current levels, the price of electricity at times of high solar output will decline. Thus the average value of solar electricity — and the profitability of solar generators — will decline with increased solar penetration. Moreover, LCOE comparisons ignore any additional costs incurred at the level of the power system as a whole to accommodate significant increases in intermittent solar generation.

<table>
<thead>
<tr>
<th>Resource</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
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<tbody>
<tr>
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<td>96</td>
<td>114</td>
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<tr>
<td>Gas Combined Cycle</td>
<td>61</td>
<td>66</td>
<td>76</td>
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<td>Onshore Wind</td>
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<td>80</td>
<td>90</td>
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<td>Solar PV</td>
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<td>130</td>
<td>201</td>
</tr>
<tr>
<td>Solar CSP</td>
<td>177</td>
<td>243</td>
<td>388</td>
</tr>
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</table>

Table 1.1 Estimated LCOEs for New Generation Resources in 2019

xxviii The ranges reflect regional differences in fuel costs and in wind and solar resources.

xxvii In addition, residential roofs are not generally optimally oriented with respect to the sun. This reduces output per unit of capacity and thus raises LCOE.
Grid-connected solar electricity exists at scale in the United States today only because it is subsidized in a variety of ways.

It follows from the cost estimates discussed above, as well as from the fact that the U.S. government does not tax or cap CO$_2$ emissions from fossil fuel combustion, that grid-connected solar electricity exists at scale in the United States today only because it is subsidized in a variety of ways. Chapters 4 and 5 review the effects of the main federal subsidies on the private costs of solar electricity. These subsidies, which consist of accelerated depreciation and an investment tax credit against corporate profits taxes, cost the government a good deal more than they benefit solar facility owners. xxviii This finding prompts our conclusion, in Chapter 9, that alternative subsidy regimes could be considerably more efficient. Together, federal tax subsidies reduce the private cost of solar electricity by about a third. State and local subsidies vary considerably, but in some cases contribute substantial additional reductions in private costs.

There are emerging technologies with considerable promise that use Earth-abundant materials and that could be deployed at large scale if their efficiency and stability could be dramatically improved.

SCALING & INTEGRATION

Chapters 6–8 of this study deal with issues that would arise if solar energy were to play a major role in electric power systems — specifically, issues of scaling and integration.

Chapter 6 provides a quantitative analysis of the materials-use and land-area requirements that would follow if solar energy were to account for a large share of global electricity production by mid-century. As the IEA scenario discussed above indicates, this would require a dramatic increase in solar generating capacity. Nonetheless, Chapter 6 suggests that the availability of commodity materials such as glass, concrete, and steel is unlikely to prove an important hindrance to PV expansion on this scale if today’s commercial technologies are employed. And, provided reliance on silver for electrical contacts can be decreased, there seem to be no significant materials-related barriers to a dramatic increase in the deployment of crystalline silicon-based PV, today’s dominant solar technology. It is important to note, however, that some thin-film PV technologies currently in use or under development rely on rare materials such as tellurium and indium. Increasing the usage of these materials far above current levels would increase their costs dramatically and perhaps prohibitively. This makes the corresponding technologies poor candidates for large-scale deployment — and thus relatively unattractive as targets for government research and development spending. On the other hand, as Chapter 2 indicates, there are emerging technologies with considerable promise that use Earth-abundant materials and that could be deployed at large scale if their efficiency and stability could be dramatically improved.

xxviii As Chapter 4 discusses, this difference arises because developers of solar projects typically need to find a partner with sufficient profits to be able to utilize the investment tax credit, and the so-called tax equity market in which such deals are done is highly imperfect.
The coordination of solar energy production and storage, through thermal storage at CSP facilities or through other means, can also help reduce the need for thermal-plant cycling and thereby increase the value of solar generation.

At higher levels of PV penetration, it will be increasingly desirable to curtail solar production (and/or other zero-variable cost production) to avoid costly variation of thermal power plants’ outputs and, in the long run, to shift the fleet of thermal generators toward more flexible technologies. The coordination of solar energy production and storage, through thermal storage at CSP facilities or through other means, can also help reduce the need for thermal-plant cycling and thereby increase the value of solar generation.

PUBLIC POLICY CHOICES

The final two chapters of this study consider government support for the development and deployment of solar technologies. Such support is generally justified as a response to two market failures: the knowledge spillovers associated with fundamental research and with experience gained through deployment, and the environmental spillovers associated with reductions in emissions of CO₂ and perhaps other pollutants that are not appropriately regulated or taxed. xxix

xxix As we discuss in Chapter 9, if total CO₂ emissions are capped, as they are in the European Union, subsidizing the deployment of solar or other renewable generation facilities raises the cost of satisfying the cap in the short run, though it may contribute to advancing solar technology and reducing institutional barriers to large-scale deployment in the longer run.
Other proposed justifications for supporting solar technologies are more difficult to rationalize as responses to market failures and are thus likely to support wasteful policies. In fact, policies that would restrict international trade in PV modules and other commodity products in order to aid domestic industry would raise the cost of using solar energy to reduce CO₂ emissions, thus hindering achievement of the key environmental objective.

Governments in the United States and abroad have devoted considerable resources to supporting the deployment of existing PV and CSP technologies and to funding research, development, and demonstration (RD&D) aimed at reducing the cost of solar electricity in the future. It is important to recognize, though, that in the United States and elsewhere, subsidies to solar are dwarfed by subsidies to other energy sources. xxx Recommending what resources the U.S. government should devote to supporting solar technology deployment and RD&D rather than pursuing other public objectives would take us well beyond the bounds of this study. It should be noted, though, that if solar electricity will be called upon to play a much greater role by mid-century than it does today, the division of any given level of spending between deployment and RD&D should be heavily influenced by expectations about the determinants of long-term costs. xxxi If, for instance, one expects that RD&D is unlikely to deliver significant breakthroughs and that future cost reductions will come primarily from efforts by manufacturers and installers, support for deployment becomes relatively more attractive. Alternatively, if one believes that RD&D on PV, CSP, and complementary technologies such as grid-level storage and solar-to-fuels technologies could produce dramatic reductions in the overall future cost of solar electricity, investment in RD&D becomes relatively more attractive.

While most members of the study team in fact favor a shift of some spending from deployment to RD&D, our analysis in Chapters 9 and 10 concentrates on how spending in each of these areas can be more efficient and effective.

If a price were imposed on U.S. CO₂ emissions to reflect the damages they cause, whether through a tax or a cap-and-trade regime, special support for the deployment of solar technologies would still be justified to the extent that such support served to advance those technologies and to overcome institutional and other barriers to large-scale deployment. Chapter 9 focuses on approaches that have been used in the United States and abroad to support solar technology deployment, including: 1) price-based policies, which affect the prices solar generators receive for their output; 2) output-based policies, which require minimum amounts of solar generation; 3) investment-based policies, which subsidize investment in solar generators; and 4) a variety of other policies that fit in none of these categories. In the United States, a wide array of support policies of all types has been and is being employed at the federal, state and local levels. What is not known, however, is how much has been spent in total by taxpayers and electricity consumers to support solar deployment.

xxx In the U.S. in fiscal 2010, for instance, direct federal subsidies to solar energy were less than those to each of coal, natural gas and petroleum liquids, nuclear, and wind and comparable to subsidies for biomass. 38

xxxI For an illustration of this sort of choice, see Payne, Duke, and Williams. 39
Federal, state, and local policies that subsidize residential solar generation more generously than utility-scale solar generation make little sense.

Because, as noted above, residential PV generation in the United States is considerably more expensive than utility-scale generation, a dollar of subsidy devoted to residential PV generation produces less solar electricity than a dollar of subsidy devoted to utility-scale generation. For this reason, federal, state, and local policies that subsidize residential solar generation more generously than utility-scale solar generation make little sense. Chapter 9 also concludes that the U.S. federal investment tax credit is considerably less efficient than a variety of alternative price-based and output-based subsidies. At the state level, more than half the states have renewable portfolio standards (RPS) that generally require firms that sell electricity at retail to acquire specified minimum fractions of that electricity from generators that have been certified as renewable. More than half of these programs have explicit requirements for, or give extra incentives for, solar power or distributed generation (which is predominantly PV).

Because all but two existing state RPS programs limit the ability to procure renewable power from distant sources, however, siting decisions for solar plants are constrained. This unnecessarily increases costs.

The last chapter of this study, Chapter 10, deals with RD&D spending aimed at improving solar technologies. Historically, the U.S. federal government has spent little on solar energy relative to other technologies with less long-run potential in a carbon-constrained world. xxxii Moreover, the level of spending on solar RD&D has varied substantially over time, significantly reducing the efficiency of the research enterprise.

Chapter 10 argues that today’s high cost of solar electricity relative to other generating technologies, plus the likely need for solar to play a much greater role in the global energy system in coming decades, implies that federal spending should focus on fundamental research aimed at

xxxii For detailed historical data on U.S. federal energy RD&D spending, see Gallagher and Anadon. 40
detail in subsequent chapters: it is generally more expensive at present to generate electricity from solar energy than from fossil fuels; the solar industry today is tiny relative to the scale it would need to attain to play a major role in the global energy system; and solar electricity is intermittent.

It seems possible with existing technologies to handle the intermittency of solar generation even at penetration substantially above current levels.

With respect to the first of these obstacles, RD&D on solar technologies has the potential to reduce their costs, perhaps substantially, and putting a price on CO2 emissions through a tax or cap-and-trade system will level the playing field between solar and fossil technologies. Particularly before a comprehensive climate policy is in place, deployment subsidies can reduce emissions and provide incentives to lower various barriers to large-scale solar deployment, and may contribute to advancing solar technology. Second, as long as solar technologies that rely on scarce materials are used only to a limited extent, there are no visible obstacles to increasing the scale of solar generation dramatically. Finally, it seems possible with existing technologies to handle the intermittency of solar generation even at penetration substantially above current levels, using flexible fossil-fueled generators, reservoir hydro and pumped storage where available, and making increased use of demand response. RD&D that substantially reduces the cost of CSP generation, with its inherent storage capability, could help in some regions. In the longer run, advances that make grid-level energy storage economical may be required to enable very high levels of reliance on solar generation.

While we are optimistic about the potential contribution of solar RD&D, and thus about the potential of solar to make a much greater contribution to global energy supply than at present, we are critical of the current pattern of U.S. government support for solar technologies. The total amount currently being spent at all levels of government to support solar deployment is unknown, but it is clear that the policies that have been employed to date produce significantly less solar generation per dollar spent than they could. Spending on solar RD&D has been low relative to spending on other energy technologies with less long-term potential, it has been variable over time, and it has been too focused on short-term gains rather than long-term reductions in the cost of solar electricity. All of these aspects of public policy can and should be improved.
REFERENCES


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