Chapter 6 – PV Scaling and Materials Use

6.1 INTRODUCTION

As discussed in Chapter 1 of this report, solar energy is one of the few primary energy sources suitable for large-scale use in a carbon-constrained world. Solar photovoltaics (PV) accounted for approximately 0.85% of global electricity production in 2013 and approximately 139 gigawatts of installed peak capacity (GWp). Given current estimates that as much as 25,000 GW of zero-carbon energy will be required by 2050 to achieve the international community’s goal of avoiding dangerous anthropogenic interference with the earth’s climate, PV deployment could be called upon to scale up by one to two orders of magnitude by mid-century.2,3

Predicting the future trajectory of any nascent technology is difficult, and PV is no exception (Box 6.1). On one hand, cumulative PV capacity worldwide has grown at roughly 47% per year since 2001 — a trend that, if it were naively projected into the future, would suggest that the entirety of the world’s electricity demand will be satisfied by PV within the next twelve years.4 A more realistic analysis, on the other hand, would recognize that while high growth rates may be easy to maintain for initially small levels of production, growth rates inevitably fall as demand begins to saturate and as deployment approaches physical limits to growth. Some bottlenecks — in PV manufacturing capacity or labor availability, for example — can be addressed rapidly and are not intrinsically limiting. Other constraints — such as the availability of critical materials or suitable land area — could conceivably present harder limits. This chapter examines potential limits on scaling PV deployment to the multiple-terawatt level, with a focus on constraints related to material production capacity and availability.

Cumulative PV capacity worldwide has grown at roughly 47% per year since 2001.

In Section 6.2 we analyze production requirements for commodity materials such as glass, aluminum, and concrete, based on a future dominated by today’s commercial PV technologies, including crystalline silicon (c-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). Since these technologies are already in use and balance-of-system (BOS) requirements are well known, it is possible to make detailed projections of materials use under different scaling scenarios. These projections are valid as long as module form factors do not change substantially. Estimates based on current silicon PV technology may constitute an upper bound on commodity materials usage; as noted in Chapter 2, some emerging thin-film technologies may be able to achieve much lower BOS requirements than silicon, perhaps by employing lightweight and/or flexible modules with thin absorber layers. Concentrating solar thermal power (CSP, discussed in Chapter 3) relies solely on such commodity materials, but given the relatively small number of large-scale CSP plants, the fact that CSP systems are less modular in nature than PV systems, and the possibility that future CSP plants could demonstrate different material requirements if higher-temperature technologies are developed, we do not consider material scaling issues for CSP here.

The analyses in this section and following sections are also discussed in a recent publication by members of the study group.5
In Section 6.3 we consider critical elements that are necessary components of certain PV technologies, but that are — in some cases — rare in the earth’s crust and/or occur only rarely in concentrated ores. Examples of such elements include silicon for c-Si PV, tellurium for CdTe, and gallium, indium, and selenium for CIGS. Unlike commodity materials, these critical materials have few, if any, substitutes in a given PV technology. In most cases they are part of the light-absorbing and charge-transporting layer; in these cases, substituting another element would amount to introducing a new PV technology. We also include silver, which is used to form the electrical contacts on silicon solar cells, in this analysis. While silver is not part of the current-generating active material of the cell and while PV industry roadmaps project the introduction of more abundant, lower-cost alternatives in the coming decade, silver currently accounts for a large fraction of the cost of silicon solar cells and provides useful context as a scarce material with a long production history.

PV technologies that employ scarce elements may encounter a deployment ceiling due to limits on cumulative production.

Section 6.4 discusses different approaches to addressing material scaling limits. Critical materials limitations could be circumvented either by reducing material intensity (grams of material per peak watt delivered) or by using more abundant materials. For some commercial PV technologies, the required reductions in critical material intensity are impractically large. These technologies may be relegated to a minor role in a dramatic expansion of PV capacity. Some emerging thin-film technologies may offer a sustainable alternative with substantially lower critical material requirements.

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ii Indium is also used in the indium tin oxide (ITO) transparent electrode for CdTe PV and many emerging thin-film PV technologies, though at less than one-quarter the intensity (measured in tons/GWp) of its use in CIGS.
BOX 6.1 SOLAR GROWTH AND COST PROJECTIONS

Each year the International Energy Agency (IEA) releases its World Energy Outlook (WEO) publication, which summarizes the current state of the world’s energy systems and makes projections for how those systems will shift in the future. The growth of solar power (PV and CSP) has consistently outstripped the IEA’s “reference scenario” projections: the 2006 WEO projection for cumulative solar capacity in 2030 was surpassed in 2012 and the 2011 WEO projection for 2020 was surpassed in 2014. Past growth projections for solar energy from the U.S. Department of Energy’s Energy Information Administration (EIA) have similarly underestimated actual growth. Even the IEA scenarios that assume more aggressive policy interventions to address global climate change (specifically, IEA’s “New Policies” and “450 ppm” scenarios), and that therefore factor in the effects of renewable energy deployment policies, have underestimated the growth of solar power. While the high rate of growth of solar power worldwide is eventually expected to slow as grid integration difficulties become more dominant (see Chapters 7 and 8), these trends highlight the possibility that solar technologies could supply a greater fraction of the future energy supply mix than current growth projections suggest.

The cost of PV installations has also fallen much more rapidly than projected. In 2014, prices for residential PV systems reached the level projected for installed PV capital costs in 2030 according to EIA’s 2009 International Energy Outlook report, and utility PV system prices have fallen even faster. Figure 6.1 shows actual solar capacity growth and recent cost trends compared to projections.

**Figure 6.1 Solar Capacity Growth and Costs Compared to Projections**

![Graph showing actual solar capacity growth and costs compared to projections.](image)

Note: In Figure 6.1a, International Energy Agency (IEA) and Energy Information Administration (EIA) projections for cumulative PV and CSP installed capacity are represented by empty colored circles and squares; actual historical data for cumulative PV and CSP installed capacity are represented by filled black circles. Dotted lines are given as guides to the eye. Projections are from the IEA World Energy Outlook reports over the period from 2006 to 2014 and the EIA Annual Energy Outlook reports over the period from 2010 to 2013; actual data for cumulative PV capacity are from EPIA and IHS, Inc.; actual data for cumulative CSP capacity are from REN21. In Figure 6.1b, observed prices are from Chapter 4 of this report; cost projections are from EIA and are presented in 2014 dollars.
Demand Projections

Any quantitative analysis of PV scaling limits must make an assumption about future electricity demand (kilowatt-hours per year [kWh/year]) and the fraction of that demand that will be satisfied by PV (the PV fraction). Multiplying demand by the PV fraction gives projected total PV generation; further dividing by an assumed capacity factor and the number of hours in a year gives the total installed PV capacity required to meet projected demand (Wp).

Projections of the fraction of electricity demand satisfied by PV at various points in the future vary widely; estimates for 2030 range from 1% to 75%.[17,21] For this analysis we do not pick a specific projection for the future energy mix, but rather estimate the peak installed capacity needed to satisfy 5%, 50%, or 100% of global electricity demand in 2050 with solar PV generation. We use these capacity projections throughout the chapter to analyze material availability constraints for different PV technologies. For a given material and technology, we can compare total material requirements in tons to current annual production in tons/year, indicating the number of years of current production that would be required to deploy a particular technology at a particular scale. We can then compare the growth rate in materials production required to meet these targets with historical growth rates in the production of a collection of metals.

Our analysis can be rescaled easily to account for different capacity targets and PV technology mixes, simply by scaling the values calculated for a 100% PV share of future generation by the desired multiple. The year 2050 is chosen to match widely cited climate change mitigation targets. In its 2°C global warming scenario, the International Energy Agency (IEA) projects that worldwide electricity demand in 2050 will total 33,000 terawatt-hours (TWh).[24] This baseline demand projection, along with an annual- and global-average PV capacity factor of 15%,[iii] is assumed for all calculations in this chapter. We make the simplifying assumption that the power system can fully utilize any amount of solar generation regardless of its temporal profile; the annual energy demand divided by the capacity factor and the length of a year then corresponds to an installed capacity of 25 terawatts (TWp) at a 100% PV fraction (in other words, assuming that PV supplies all 33,000 TWh of projected global electricity demand).

Land Use

Given the diffuse nature of the solar resource, it might be expected that land constraints would constitute a barrier to scaling PV deployment to a level sufficient to meet a large share of U.S. or global electricity demand. This point and the details of our analysis are addressed in Appendix A, but we briefly discuss the chief findings here.

As an example, we consider supplying all of U.S. electricity demand in the year 2050, projected to total roughly 4,400 TWh (or 0.5 TW averaged over the course of a year),

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[iii] Current annual-average PV capacity factors range from approximately 10% in Germany[25] to approximately 20% in the United States.[26] The difference is primarily due to differences in insolation. Global-average capacity factors will likely increase with time, as deployment is expanding fastest in countries with higher insolation than Germany. With global-average solar irradiance over land at 183 watts per square meter (W/m²)[21] and a typical direct-current-to-alternating-current (dc-to-ac) derate factor of approximately 0.8, we expect the long-term global average capacity factor to approach approximately 15%.
with PV. The land area that must be dedicated to PV in this case is indeed large — roughly 33,000 square kilometers (km²), or 0.4% of the land area of the United States. Nevertheless, this figure is comparable in magnitude to land areas currently employed for other distinct uses in the United States, as shown in Figure 6.2.

Some comparisons in Figure 6.2 are worth noting. For example, the land area required to supply 100% of projected U.S. electricity demand in 2050 with PV installations is roughly half the area of cropland currently devoted to growing corn for ethanol production, an important consideration given the neutral or negative energy payback of corn ethanol and other complications associated with this fuel source. That same land area — i.e., 33,000 km² to supply 100% of U.S. electricity demand with PV — is roughly equal in size to the area that has been disturbed by surface mining for coal, and it is less than the land area occupied by major roads. The currently existing rooftop area within the United States provides enough surface area to supply roughly 60% of the nation’s projected 2050 electricity needs with PV.

It is also worth noting that PV installations do not necessarily monopolize land area, but can share land currently employed for other uses. Rooftop installations are an obvious example of dual use; livestock pastures can be combined with sparse solar tracking installations, and many highway and power line rights-of-way could accommodate PV installations in currently underutilized buffer zones.

### 6.2 Commodity Materials

We use the term “commodity materials” to refer to common materials that are used in PV modules and systems but that are not intrinsically required for solar cell operation. These materials share a number of properties that distinguish them from PV-critical materials.

Following an analysis by the U.S. Department of Energy’s National Renewable Energy Laboratory, we classify six materials frequently used in PV facilities as commodity materials:

- Flat glass – encapsulation for modules, substrate for thin-film PV
- Plastic – environmental protection
- Concrete – system support structures
- Steel – system support structures
- Aluminum – module frame, racking, supports
- Copper – wiring

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*The land area required to supply 100% of projected U.S. electricity demand in 2050 with PV installations is roughly half the area of cropland currently devoted to growing corn for ethanol production.*

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*In 2013, ethanol contributed just under 7% of the energy content of U.S. gasoline.*

*Some of this land has since been reclaimed for other uses.*

*According to Denholm and Margolis, the major road distinction “includes interstate, arterial, collector, and urban local roads. Does not include rural local and rural minor collector roads. These minor roads have a large area, but are not included due to data uncertainties, especially regarding lane width.”*

*Including all thermoplastics and thermosets as listed by the American Chemistry Council.*
Table 6.2 Land Requirements for Large-Scale PV Deployment Compared to Existing Land Uses

<table>
<thead>
<tr>
<th>U.S. land area devoted to:</th>
<th>Area of the state of Massachusetts</th>
</tr>
</thead>
<tbody>
<tr>
<td>National parks (340)</td>
<td></td>
</tr>
<tr>
<td>Corn ethanol (66)</td>
<td></td>
</tr>
<tr>
<td>Defense (121)</td>
<td></td>
</tr>
<tr>
<td>Military testing ranges (21)</td>
<td></td>
</tr>
<tr>
<td>Coal mining (34)</td>
<td></td>
</tr>
<tr>
<td>Major roads (49)</td>
<td></td>
</tr>
<tr>
<td>Rooftops (20)</td>
<td></td>
</tr>
<tr>
<td>Golf courses (10)</td>
<td></td>
</tr>
</tbody>
</table>

Note: The solar land requirement is calculated assuming that solar PV generation is used to meet 100% of projected 2050 U.S. electricity requirements (roughly 0.5 TW averaged over a year). Details of the calculation are given in Appendix A. Figures for other land areas represent actual current uses, and numbers in parentheses denote thousands of square kilometers of area. All elements of the figure are to scale.

These materials are mined and/or produced as primary products at scales above 10 million (1x10^7) tons per year. The primary influences that govern their long-term global production are thus market conditions and production capacity rather than material abundance. These commodity materials are used in a variety of non-PV applications and are transferable between different end uses with little change in form; for example, the concrete and copper.

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viii Land classes (“urban,” etc.) are taken from U.S. Department of Agriculture.34 “National parks” is from the National Park Service.35 “Corn ethanol,” “major roads,” “rooftops,” and “golf courses” are from Denholm and Margolis.32 “Defense” is from the U.S. Department of Defense.36 “Military testing ranges” corresponds to the sum of the net land area given by Wikipedia for four distinct U.S. testing ranges: Utah Test and Training Range (6,930 km²), White Sands Missile Range (8,300 km²), McGregor Range Complex (2,400 km²), and Yuma Proving Ground (3,387 km²). “Coal mining” corresponds to the net land area that has been disturbed by surface mining for coal and is taken from multiple sources.29-31 This chart was developed in conjunction with MIT subject ESD.124, “Energy Systems and Climate Change Mitigation.”
wiring used in a PV array are no different from the concrete and copper wiring used in the construction of an office building.

Here we estimate commodity materials requirements as a function of the fraction of global electricity demand satisfied by PV, assuming commodity material intensities representative of current commercial PV technologies (c-Si, CdTe, and CIGS). Estimated materials requirements can be translated into multiples of current annual production, or into required annual growth rates until 2050. Comparing these projections with historical growth rates may help to identify potential limits on PV deployment stemming from the availability of commodity materials. However, it is important to note that future demand for commodity materials from other applications is difficult to predict, and that PV applications currently account for only a small fraction of total demand for each of the major commodities considered in our analysis.

Figure 6.3 shows the cumulative amount of each commodity material that would have to be produced between now and 2050 in order to deploy sufficient PV capacity to satisfy 5%, 50%, and 100% of global electricity demand in 2050 (corresponding to 1.25 TWp, 12.5 TWp, and 25 TWp of installed PV capacity, respectively, under the assumptions noted in Section 6.1). By comparing these numbers (plotted against the horizontal axis of Figure 6.3) with the current total annual production of each commodity material

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**Figure 6.3 Commodity Materials Requirements for Large-Scale Deployment of Current PV Technologies (Primarily Silicon)**

Note: Figure 6.3 shows, for each of six commodity materials, current total annual production (against the vertical axis) and the total amount of material required to deploy sufficient solar PV capacity to satisfy 5%, 50%, or 100% of projected global electricity demand in 2050 (against the horizontal axis). Gray dashed lines indicate the number of years of current production required to satisfy a cumulative material target. Only flat glass, and to a lesser extent, copper and aluminum would require a significant expansion or redirection of current production to achieve estimated commodity material requirements under the 100% solar PV scenario. Current annual production levels for copper, aluminum, steel, glass, plastic, and concrete are taken from the literature; material intensity numbers are derived from NREL.
(plotted against the vertical axis), we can estimate the extent to which existing commodity material markets would have to expand to accommodate global PV demand. For example, current PV modules employ flat glass sheets as substrates and encapsulation layers. To satisfy 50% of projected 2050 world electricity demand with today’s PV technologies would require 626 million ($6.26 \times 10^8$) metric tons of glass (red dot in Figure 6.3). At today’s worldwide flat-glass production level of 61 million metric tons per year, approximately 10 years’ worth of extra production would have to be allocated for PV applications between now and 2050 to achieve 50% PV penetration, as indicated by the position of the red dot near the gray dotted line labeled “10 years” in the figure. In other words, flat-glass production would, on average, need to be 29% higher than its current value for the next 35 years to satisfy flat-glass demand for the 50% PV penetration case (assuming the demand for flat glass from all other end-use sectors does not change).

In sum, there appear to be no major commodity material constraints for terawatt-scale PV deployment through 2050. This rule tends to apply generally: growth rates in production capacity for commodity materials are usually not limited by raw materials, but rather by factors such as the availability of good production sites and skilled personnel. For some commodities, such as glass, aluminum, and copper, the amount of material required to support solar PV deployment at a level sufficient to meet 100% of projected global electricity demand in 2050 (i.e., 25 TW, installed capacity) exceeds six years at current annual production levels. This result suggests that large-scale PV deployment may eventually become a major driver for these commodity markets. More limiting materials constraints may arise for the so-called PV-critical elements that are in most cases directly responsible for the solar energy conversion process in PV modules. These critical-element constraints are considered in the next section.

**FINDING**

PV modules will become a major driver of flat-glass production at high solar penetration levels, but the availability of commodity materials imposes no fundamental limitations on the scaling of PV deployment for scenarios in which a majority of the world’s electricity is generated by PV installations in 2050.

### 6.3 CRITICAL MATERIALS

The PV technologies described in Chapter 2 make use of chemical elements that differ greatly in abundance, yearly production, and historical rates of production growth. For example, silicon is the second most abundant element in the earth’s crust, while tellurium is estimated to be about one-quarter as abundant as gold. In 2012, the world produced 7.8 million tons of silicon and just 380 tons of gallium. And the production of indium has grown at an average annual rate of 9.8% over the past 20 years, while selenium production has grown at a rate of just 1.2% per year.

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**ix** Military aircraft production in the United States grew by one-to-two orders of magnitude between 1939 and 1944, highlighting the tremendous level of growth that is possible for commodity-based goods.
The large-scale deployment of solar power systems that employ scarce elements would vastly increase demand for these resources. Unlike many other aspects of solar power systems, the use of scarce elements does not benefit from economies of scale. On the contrary, because these elements are genuinely scarce, their contribution to the cost of solar energy technologies is likely to increase with the scale of deployment in ways that are difficult to predict or control. This section examines the possible constraints on PV deployment presented by six PV-critical elements: silicon and silver in c-Si solar cells; tellurium in CdTe solar cells; and gallium, indium, and selenium in CIGS solar cells. For each of these elements we consider potential constraints on cumulative production in tons, yearly production in tons per year, and growth in yearly production in tons-per-year per year, and we compare future production requirements with physical limits and historical experience.

### Cumulative Production [tons]

Table 6.1 summarizes data on the relative crustal abundance of the six PV-critical elements (as a fraction of the weight of the earth’s crust), cumulative world production from 1900 to 2012, and levels of cumulative production required to support future PV deployment at a scale commensurate with 100% PV penetration by mid-century.

The use of scarce elements does not benefit from economies of scale.

It should be noted that the absolute amount of any of these PV-critical elements in the earth’s crust is not expected to constrain future PV deployment. For example, even if CdTe PV installations are used to supply 100% of projected global electricity demand in 2050, the quantity of tellurium required would amount to roughly one ten-millionth (1/10,000,000)

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance [fraction]</th>
<th>Cumulative production (1900–2012) [10^6 tons]</th>
<th>Cumulative amount in PV by 2050 for 100% PV penetration [10^6 tons]</th>
<th>Ratio of 2050 PV cumulative production to cumulative 1900–2012 production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>0.28</td>
<td>0.32</td>
<td>0.53</td>
<td>76</td>
</tr>
<tr>
<td>Silver</td>
<td>7.5 × 10^-6</td>
<td>1.1</td>
<td>0.60</td>
<td>0.79</td>
</tr>
<tr>
<td>Tellurium</td>
<td>1.0 × 10^-9</td>
<td>0.010</td>
<td>0.010</td>
<td>0.0026</td>
</tr>
<tr>
<td>Gallium</td>
<td>1.9 × 10^-5</td>
<td>0.023</td>
<td>0.023</td>
<td>0.0013</td>
</tr>
<tr>
<td>Indium</td>
<td>2.5 × 10^-7</td>
<td>0.010</td>
<td>0.010</td>
<td>0.0007</td>
</tr>
<tr>
<td>Selenium</td>
<td>5.0 × 10^-8</td>
<td>0.032</td>
<td>0.032</td>
<td>0.0032</td>
</tr>
</tbody>
</table>

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xPrevious work along the same lines can be found in Andersson et al., NREL PV-FAQs, Feltrin et al., Green, Zweibel, and Wadia. For an introduction to energy critical elements, see Jaffe and Price, National Research Council, and DOE.

xiOur data on silicon production include both metallurgical grade silicon, which is the present feedstock for c-Si PV applications, and ferrosilicon, a lower-purity alloy used primarily in steel manufacturing. Our method of analysis implicitly assumes that ferrosilicon production could be redirected toward metallurgical grade silicon if demand were sufficient. If silicon currently used in ferrosilicon production could not be directed toward metallurgical grade silicon production, then higher rates of growth in silicon production would be required to meet our stated PV deployment targets.

xiiStated abundances are taken from the CRC Handbook of Chemistry and Physics, but it should be noted that there is naturally some uncertainty in these values and different estimates are available from other sources. The range of estimates for the crustal abundance of the six PV-critical elements across six different references are: silicon, 0.27–0.30; silver, 7.0–8.0 × 10^-6; tellurium, 1.0–2.0 × 10^-5; gallium, 1.7–1.9 × 10^-5; indium, 0.5–2.5 × 10^-7; selenium, 5.0–15 × 10^-8. Our conclusions are not sensitive to the range of uncertainty displayed across these data sets.
of the tellurium estimated to be present in the earth’s crust. However, the mining of any element\textsuperscript{xiii} is only economical when that element is concentrated at ratios well above its average concentration. If all deposits were known and competition were perfect, then, as the most concentrated deposits were depleted, production would shift to less and less concentrated deposits and production costs would rise. Geopolitical factors, improvements in exploration and extraction techniques, and the economics of byproduction can all complicate this simple picture.

A detailed analysis of the \textit{economically recoverable} fraction of different PV-critical elements as a function of PV demand is beyond the scope of this study, but a comparison of the relative abundances of these elements provides a useful sense of scale when considering different PV technology options as candidates for large-scale deployment. Silicon is 20,000 times as abundant as gallium (the next most abundant PV-critical element) and 300 million times as abundant as tellurium; to supply 100% of projected global electricity production of silver since 1900. Complete reliance on CdTe or CIGS PV at current material intensities, on the other hand, would require the production of roughly 76 times more tellurium and 43 times more gallium, respectively, for use in PV installations than has ever been produced for all other uses combined.

\textbf{Yearly Production [tons/year]}

Current rates of production for PV-critical elements provide a more useful point of reference than relative crustal abundances when considering questions of scale. As discussed below, yearly production and price are not necessarily linked to abundance: selenium, for example, costs less and is more copiously produced than gallium and indium, even though it is the least abundant of the three. The current economics of PV-critical elements is primarily dictated by the fact that, with the exception of silicon, these elements are typically produced as byproducts of other, more common elements. We begin by comparing the amount of material required to support our three 2050 PV deployment targets with current rates of production of the six PV-critical materials considered here. We then apply a similar analysis to critical materials for battery energy storage. Finally, we elaborate on the economics of byproduction.

The current economics of PV-critical elements is primarily dictated by the fact that, with the exception of silicon, these elements are typically produced as byproducts of other, more common elements.

Figure 6.4, which follows the same format as Figure 6.3, compares the total quantities of key elements required to satisfy 5%, 50%, and 100% of projected world electricity demand in 2050 with wafer-based, commercial thin-film, and emerging thin-film PV technologies.

For example, supplying 100% of projected global electricity demand in 2050 with c-Si PV would require roughly one-third as much silicon as has already been produced since 1900. While silver is one of the least abundant elements considered here, it has been highly valued for millennia and primary mining of silver is a well-established industry. The amount of silver required to support c-Si PV deployment at the scale required in the 100% penetration case, assuming current material intensities, would correspond to roughly half the global cumulative

\textsuperscript{xiii} Apart, perhaps, from the eight major rock-forming elements (oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium), which are all present at abundances above 2% in the earth’s crust.
Material intensity values are calculated using typical device structures and absorber compositions, assuming 100% materials utilization and cell manufacturing yield and module efficiencies equal to current lab-cell record efficiencies, as discussed in Chapter 2. (These assumptions are optimistic and could underestimate the amount of material required, but they serve as a simple and traceable point of comparison.) Material intensities are calculated for III-V multi-junction (MJ) solar cells based on the standard triple-junction structure described in Chapter 2, for a-Si:H cells based on an a-Si:H/nc-Si:H/nc-Si:H triple-junction, for CIGS based on a Cu:In:Ga:Se stoichiometry of 1:0.5:0.5:2, and for perovskite cells based on the mixed-halide perovskite CH$_3$NH$_3$PbI$_2$Cl. The boxes and ovals for c-Si represent the range spanned by single- and multi-crystalline silicon cells. A concentration ratio of 500x is assumed for III-V MJ solar cells. Organic and dye-sensitized solar cells require only abundant elements and are omitted.

Note: For each PV technology, Figure 6.4 shows the quantities of key elements required to satisfy 5%, 50%, or 100% of projected global electricity demand in 2050, corresponding to a total installed capacity of 1.25 TW$_p$, 12.5 TW$_p$, or 25 TW$_p$. Gray dashed lines indicate material requirements as a multiple of current annual production. Technologies that tend away from the lower-right corner of each plot can achieve terawatt-scale deployment without substantial growth in annual production of constituent elements.

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$x^{iv}$ Material intensity values are calculated using typical device structures and absorber compositions, assuming 100% materials utilization and cell manufacturing yield and module efficiencies equal to current lab-cell record efficiencies, as discussed in Chapter 2. (These assumptions are optimistic and could underestimate the amount of material required, but they serve as a simple and traceable point of comparison.) Material intensities are calculated for III-V multi-junction (MJ) solar cells based on the standard triple-junction structure described in Chapter 2, for a-Si:H cells based on an a-Si:H/nc-Si:H/nc-Si:H triple-junction, for CIGS based on a Cu:In:Ga:Se stoichiometry of 1:0.5:0.5:2, and for perovskite cells based on the mixed-halide perovskite CH$_3$NH$_3$PbI$_2$Cl. The boxes and ovals for c-Si represent the range spanned by single- and multi-crystalline silicon cells. A concentration ratio of 500x is assumed for III-V MJ solar cells. Organic and dye-sensitized solar cells require only abundant elements and are omitted.
tons and 785,000 metric tons, respectively. Both elements thus appear at roughly the same position along the horizontal axis (notice that both axes are logarithmic). But current annual production of cadmium (at 21,800 tons/year) exceeds that of tellurium (at 525 tons/year) by two orders of magnitude. As a result, the points for tellurium appear well below those for cadmium on the vertical axis. Deploying 25 TWp of CdTe PV capacity would require the equivalent of 35 years of global cadmium production and 1,400 years of global tellurium production at current rates, as indicated by the diagonal gray lines in Figure 6.4b.

It is important to note that large-scale integration of solar and other intermittent, non-dispatchable renewable energy technologies will likely require large-scale deployment of grid-scale energy storage (see Appendix C), which would also carry critical material requirements. Rechargeable batteries are leading candidates for such applications, and since the energy capacity of a battery is proportional to the mass of active material used, grid-scale deployment may significantly increase the demand for some raw materials. Box 6.2 applies the analysis method described here for PV critical materials to critical materials for battery energy storage.

**BOX 6.2 MATERIALS SCALING FOR BATTERY ENERGY STORAGE**

To quantify material requirements for widespread deployment of several commercial and emerging battery technologies we apply the same approach used in this chapter to analyze commodity and PV-critical materials scaling issues. Battery technologies differ primarily in the active materials used in the positive and negative electrodes — each possible pair is known as a battery couple. Battery couples are grouped into aqueous, high temperature, lithium-ion (Li-ion) and lithium-metal (Li-metal), flow, and metal air technologies, as shown in Figure 6.5.

For each battery couple, we calculate the amount of key limiting elements theoretically required to store 1% (0.9 TWh), 10% (9 TWh), or 55% (50 TWh) of projected global daily electricity demand in 2050, where 55% corresponds roughly to the storage capacity required to enable 100% solar electricity generation under typical U.S. demand patterns. The analysis of limiting elements is adapted from Wadia et al., based on the element in each couple that limits the potential annual production of batteries based on that couple, assuming all of the material is used to make batteries. Gray dashed lines indicate material requirements as a multiple of current annual worldwide production.

Technologies that tend away from the lower-right corner of each plot can achieve multi-TWh deployment scale without substantial growth in annual production of constituent elements. For lead-acid (Pb/PbO2) battery couples, several zinc-based couples, and many Li-ion technologies, less than 35 years’ worth of material production is needed to store 10% of projected 2050 daily electricity demand. Sodium sulfur (NaS) technologies could store 55% of daily demand using less than eight months’ worth of global sulfur production.

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xv To calculate storage capacity requirements as an average fraction of daily electricity demand in a 100% solar generation scenario, we start with data for hourly solar insolation and electricity demand profiles over a typical year in several U.S. cities and regional grids. We normalize the profiles such that the total insolation and electricity demand throughout the year are equal. Assuming that solar generation is proportional to insolation and no self-discharge occurs, the total energy that must be stored is equal to the sum of (insolation – demand) over daytime hours when the normalized insolation — i.e., solar production — exceeds demand. Dividing the total energy stored by the total demand gives the fraction of annual electricity that must be stored (55%). This fraction corresponds roughly to the daily fraction of energy stored, ignoring seasonal and day-to-day differences in daily insolation.

xvi Supplementary information provided by Paul Albertus.58
Figure 6.5 Materials Requirements for Large-Scale Deployment of Energy Storage Based on Various Electrochemical Battery Technologies

Battery couple Limiting element
Pb/PbO₂ [Pb] 1% 10% 55%
(900 GWh) (9 TWh) (50 TWh)
Fraction of global daily electricity demand in 2050

Note: Battery technologies considered here are described in more detail in Appendix C. This analysis considers only current annual production; relative crustal abundance also varies widely for the materials included in these charts. Analysis adapted from Wadia et al. Supplementary information provided by Paul Albertus.
There is no fundamental limit on the yearly production of these elements until cumulative production begins to approach crustal abundance. However, the economics of byproduction could put an effective limit on the rate of production of many PV-critical elements until the price of these elements increases enough to warrant primary mining and production. The next section discusses the economics of byproduction, which will likely determine the availability of many PV-critical elements for some time.

**Byproduction**

Most scarce elements are rarely found in concentrations high enough to warrant extraction as a primary product at today’s prices: only a handful of rare elements, such as gold, the platinum group elements, and sometimes silver, are so highly valued that they are mined as primary products. With the exception of silver and silicon, all of the critical elements used in PV systems installed today are currently obtained as byproducts of the mining and refining of more abundant metals. Table 6.2 summarizes data on the scale of annual production of these byproducts relative to their parent products.

Producing an element as a byproduct is typically much less expensive than producing the same element as a primary product. The costs of investment capital, mine planning, permitting, extraction, haulage, and several steps in the refining process are borne by the primary product. The byproduct accumulates at some stage in the refining process, and if its price exceeds the incremental cost of extracting it from other byproducts and purifying it, the byproduct is sent off for further processing at a secondary location. Even though a rare element may be relatively concentrated in the ores of several major metals (for example, tellurium is found in copper, zinc, and lead ores, among others) the market in many cases has settled on one principal source, either as a result of

**Table 6.2 Production Volume and Monetary Value of PV-Critical Elements Produced as Byproducts, Relative to Parent Products**

<table>
<thead>
<tr>
<th>Parent source</th>
<th>Tellurium</th>
<th>Gallium</th>
<th>Indium</th>
<th>Selenium</th>
<th>Silver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global production of parent in 2012 (10^3 tons)</td>
<td>17,000</td>
<td>46,000</td>
<td>14,000</td>
<td>17,000</td>
<td>17,000 (copper)</td>
</tr>
<tr>
<td>Global production of byproduct in 2012 (10^3 tons)</td>
<td>0.53</td>
<td>0.38</td>
<td>0.78</td>
<td>2.2</td>
<td>26 (silver)</td>
</tr>
<tr>
<td>Value of 2012 parent production (billion 2012$)</td>
<td>140</td>
<td>100</td>
<td>28</td>
<td>140</td>
<td>140 (copper)</td>
</tr>
<tr>
<td>Value of 2012 byproduct production (billion 2012$)</td>
<td>0.08</td>
<td>0.20</td>
<td>0.51</td>
<td>0.27</td>
<td>26 (from all sources)</td>
</tr>
</tbody>
</table>
mineralogical affinities or currently dominant refining technologies. Several aspects of joint production make the demand–price function for byproduced energy-critical elements (ECEs) volatile and difficult to predict:

**Production ceiling** – As shown in Table 6.2, the ECE market typically represents a minute fraction of the market for the primary metal. A demand-driven increase in the price of an ECE would initially be expected to spur increased recovery from the primary product stream. Once that recovery was optimized, however, ECE production could not be expanded further without increasing production of the primary product, which is unlikely in light of the current ratio of economic value between the primary product and the byproduct.xvii If the price of the ECE rises to a sufficiently high level, primary production could eventually become economical and the roles of primary product and byproduct could switch. In that case, however, such a large increase in price would almost certainly preclude the use of the ECE in PV systems.

**Changes in extraction technology** – Economic or technical developments relating to the primary product may either increase or decrease recovery of the byproduct. For instance, in-situ leaching of copper ores, which increases copper yield but does not capture tellurium, is becoming more widespread and is replacing present electrolytic refining methods, which do capture tellurium. This development could result in a lower economical production ceiling for tellurium.

**Price volatility** – To satisfy increasing demand for an ECE after economical byproduction from the current source has been maximized, a new source for the ECE would have to be developed. Until the new byproduction stream comes online, the ECE will be expensive and in short supply. If demand and price continue to increase this cycle would repeat until, eventually, primary production would be the only way to accommodate growing demand. The price required to support primary production is difficult to estimate.

Some of these issues are summarized in the hypothetical cost/production function sketched in Figure 6.6. While neither the horizontal nor the vertical scale is specified, the vertical scale is labeled “logarithmic” to emphasize the magnitude of possible fluctuations. Understanding the cost versus production curves for ECEs in more depth and producing more realistic graphs for specific ECEs in particular should be a subject for future research.

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xvii As an example, in 2005 the U.S. Geological Survey (USGS) estimated that the total quantity of tellurium that could be recovered from electrolytic copper refining at present production rates was roughly 1,200 tons/year; yields typically range from 35% to 55% today, however, which further reduces the recoverable amount of tellurium. The most optimistic scenario we could find for future tellurium production predicts that worldwide primary production of tellurium (without recycling) will peak at roughly 3,200 tons/year in 2055 and decline thereafter.60 Even if tellurium intensity falls with time, recycling from decommissioned PV modules cannot satisfy more than a fraction of exponentially growing demand from large-scale deployment.
Just as there may be limits to the cumulative or yearly production of a material, there may also be limits to the rate at which production of this material can grow. The aggressive increase in annual PV deployment required to meet 50% or 100% of projected global electricity needs with PV would necessitate similarly aggressive growth in the production of certain materials (particularly materials that do not see wide use in other sectors, such as tellurium).

Following the analysis method of Kavlak et al.\textsuperscript{51,62} (presented in more detail in an associated white paper\textsuperscript{63}), we estimate the rate of growth in the production of PV-critical elements that is necessary to achieve these PV deployment targets and compare these growth rates with historical precedent. This analysis provides insight into the feasibility of terawatt-scale deployment of different PV technologies that employ these elements.

Figure 6.7 shows production data for 35 different metals over the last century.\textsuperscript{39,44} To determine the historical rate of growth in production as a function of time, we fit lines to the natural logarithm of production in overlapping 36-year periods (equal to the time remaining to achieve our 2050 deployment targets), using the slope to determine the annual growth rate over that period. We find that the median annual growth rate of production for these 35 metals over 36-year periods between 1900 and 2012 is...
Unfortunately, data on present levels of tellurium production are fragmentary. The USGS Mineral Commodity Summaries stopped reporting world tellurium production in 2006 when non-U.S. world production was estimated to total nearly 130 tons/year (U.S. data were withheld starting in 1976 to avoid disclosing data proprietary to U.S. companies). Specific USGS Minerals Yearbook assessments estimated world (including U.S.) tellurium production at 450–500 tons/year for the period 2007–2010, 500–550 tons/year for 2011, and 550–600 tons/year for 2012. All reported data are included here; the 36-year fits used in our analysis smooth out the discontinuity.
2.8%. Out of 1,770 overlapping 36-year periods for the different metals, 26% of those 36-year periods showed annual growth rates above 5%, and only 5.8% showed growth rates above 10%. No 36-year periods with annual growth rates above 12% for a given metal have been witnessed for periods ending later than 1968. High 36-year average annual growth rates generally only occur near the onset of commercial production of a given metal, rather than after production has become well established.

**Required growth rates for silicon and silver production fall well within the range of historical growth rates, even for 100% silicon PV penetration.**

How do these historical rates of growth in production compare to the growth rates of PV-critical elements required to produce enough PV modules to supply a given percentage of projected world electricity demand by 2050? To answer this question we must account for demand from both the PV and non-PV sectors and make assumptions about how demand in both categories will change between now and 2050. As noted in the introduction to this chapter, roughly 25 TW_{p} of cumulative PV capacity would have to be installed to supply 100% of projected world electricity demand in 2050. By comparison, roughly 139 GW_{p} or 0.139 TW_{p} of PV capacity were installed worldwide by the end of 2013, with 39 GW_{p} installed during the 2013 calendar year. In this analysis we assume the installation of PV modules with the same efficiency as current record-efficiency PV cells and utilize current values for material intensity (measured in milligrams per watt of PV capacity [mg/W_{p}], or, equivalently, in tons per gigawatt [tons/GW_{p}]). Box 6.3 provides additional detail about the methodology and assumptions used in this analysis.

In Figure 6.7d, the required production growth rates for the six PV-critical elements for the 5%, 50%, and 100% PV penetration targets are compared to the histogram of historical growth rates for the 35 metals from Figures 6.7a,b. Very different trends are evident across the six PV-critical elements:

- Required growth rates for silicon and silver production fall well within the range of historical growth rates, even for 100% silicon PV penetration. Coupled with the fact that silicon is the second most abundant element in the earth’s crust, our analysis indicates that there are no fundamental barriers to scaling up silicon production to the level necessary to achieve 100% PV penetration by mid-century. Silver’s scarcity and cost imply that it is a more limiting material for silicon PV than silicon.

- Between gallium, indium, and selenium, indium would require the highest rate of production growth to meet the PV capacity targets considered here: specifically, global indium production would have to grow at a rate of 11% and 12% annually to meet the 50% and 100% CIGS penetration targets, respectively. These levels of growth are rare among the 35 metals considered here, and

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xix A key feature of exponential (or compound annual) growth in production is that both annual production and the cumulative amount produced grow exponentially; in linear growth, annual production stays constant. The 5% PV penetration target in 2050 can be reached with constant annual production of PV modules (39 GW_{p}/year × 36 years = 1.4 TW_{p}); actual annual installation of PV worldwide has demonstrated a roughly 50% annual growth rate over the past 12 years, albeit from a very small initial value.4

xx Copper is the intended substitute for silver in silicon PV, and is expected to mostly replace silver within the next decade.6
have not been witnessed within the last 40 years. Even supplying just 5% of global electricity demand in 2050 with CIGS solar cells would require 10% annual growth in

indium production over the next 36 years, which is in the top 6% of historical growth rates demonstrated by the 35 metals considered here.\textsuperscript{xii}

\textsuperscript{xii}If the median historical growth rate of all 35 metals (2.8\%) is used instead of the metal-specific historical growth rates, the resulting required growth rates for the 100\% PV cases are changed by no more than ±1\% in absolute terms for silicon, silver, tellurium, gallium, and selenium, and by -2.3\% in absolute terms for indium.

\textsuperscript{xiii}The production of indium has grown rapidly in recent years in response to increasing demand from the consumer electronics industry, where it is used (in the form of indium tin oxide, or ITO) in the fabrication of flat-panel displays. Yet indium is also one of the least-produced metals considered here (at 780 tons/year it is 29th on our list of 35 metals), and given the potential complications with its status as a byproduced element, it may meet production limitations. Alternatives such as fluorine-doped tin oxide (FTO) are available to replace indium in transparent electrodes, and copper zinc tin sulfide (CZTS) is being explored as an alternative active material to CIGS.
Tellurium would require the highest rate of production growth among the materials considered here, with 12% and 15% annual production growth required to meet the 50% and 100% CdTe penetration targets.

**FINDING**
The growth of silicon production necessary to supply even 100% of projected 2050 world electricity demand with PV falls well within historical levels. Silver is more limiting than silicon for silicon PV, and reducing or phasing out the use of silver should be a high priority for silicon PV research and development.

**FINDING**
Supplying even 5% of world electricity demand with cadmium telluride (CdTe) or copper indium gallium selenide (CIGS) solar cells would require directing today’s entire worldwide production of key elements (tellurium, indium, and gallium) to PV fabrication. There is little historical precedent for the rates of growth in metal production that would be necessary to support higher levels of CdTe or CIGS penetration.

We note that growth rates reflect not only supply but also demand: if prices are relatively stable, demand will determine growth. Thus, low historical rates of growth in the production of a particular material do not necessarily imply that an unprecedented increase in demand for that material could not be met by a similarly unprecedented increase in supply. For example, molybdenum production grew by 19% annually between 1907 (when molybdenum production totaled 91 tons) and 1943 (when molybdenum production totaled 31,600 tons); this rapid increase in production occurred in response to demand for molybdenum steel armor plating during World Wars I and II. Such high growth rates in the production of specific metals are, however, rare outside the high demand levels present during wartime mobilization.

**6.4 ADDRESSING MATERIAL SCALING LIMITS**

As discussed in the foregoing sections, our analysis suggests that silicon does not face any fundamental limits in terms of cumulative production, yearly production, or growth in production even if silicon-based solar cells are used to meet 100% of projected global electricity demand by 2050. Silver faces intermediate constraints in some of these areas, and tellurium, indium, gallium, and selenium each face more severe constraints. We next consider approaches to mitigating potential limits to the scaling of materials production for large-scale PV deployment: first, by decreasing the material intensity of presently-used elements, and second, by developing presently emerging thin-film technologies that make use of more abundant and widely-produced elements.

**Decreased Material Intensity**

**Silver**

The cost of silver already adds to silicon PV module costs significantly: silver accounts for approximately 10% of the non-silicon cell cost, and 5%–10% of the world’s new silver production is already being used for PV manufacturing. The International Technology Roadmap for
Photovoltaic 2014 Report (ITRPV) envisions silver intensity decreasing from 24 tons/GWp today to approximately 7 tons/GWp by 2024. As shown in Figure 6.8a, if silver intensity were reduced to the ITRPV predicted value of 7 tons/GWp, continued production of silver at the present rate would supply sufficient silver to enable 50% PV penetration within 3.4 years if all silver production were used for PV manufacture. In other words, if total silver production persisted at present levels, the silver required for 50% PV penetration in 2050 would make up 9.4% of overall silver production for the next 35 years. We conclude that the

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Note: Current material intensities are designated by the red curves, and various projected values for material intensity (tons/GWp) are shown for silver (Ag) for c-Si PV (a), tellurium (Te) for CdTe (b), and indium, gallium, and selenium (In, Ga, and Se) for CIGS (c-e). Future material intensities are calculated from known densities and relative mass fractions of the relevant elements, along with estimated materials utilization (90% for Te; 34% for In, Ga, and Se), projected active layer thicknesses, and projected power conversion efficiencies. Annual production data for each element are from the U.S. Geological Survey (USGS). For the 50% solar PV case (dashed vertical lines; 12.5 TWp total deployment), we indicate the number of years of current material production required to deploy each PV technology given different material intensity values.

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We note that the data in Figure 6.8, following the analysis in ITRPV, Woodhouse et al., and Fthenakis, reflect assumptions based on module efficiencies; Figures 6.4 and 6.7 utilize record cell efficiencies and are therefore more optimistic.
reduction of silver intensity or the substitution of a more abundant element (such as copper, which is the PV industry’s intended substitute) in c-Si PV cells should be a high research priority.

CdTe

The situation for tellurium in CdTe thin-film PV is not as favorable as the situation for silicon and silver in c-Si PV. Figure 6.8b shows scenarios for CdTe deployment assuming different potential tellurium intensities. Unless tellurium intensity can be decreased even beyond today’s optimistic projections and/or unless a major and unanticipated new supply of tellurium emerges, deployment of CdTe solar cells at a level sufficient to meet a large fraction of electricity demand in 2050 may be out of reach, even if 100% of the world’s tellurium output from known sources were directed toward PV fabrication. Of course, at a much lower rate of deployment — as might be appropriate if CdTe were only one component of a suite of PV technologies — tellurium supplies would not be a constraint.

CIGS

Materials supply prospects for large-scale deployment of CIGS PV fall somewhere between the prospects for c-Si and CdTe deployment. Figures 6.8c-e show demand for indium, gallium, and selenium, respectively, as a function of proposed deployment and material intensity. It should be noted that since all three elements are necessary components of CIGS solar cells, the deployment of this technology would be limited by the element with the lowest production. Since gallium has the lowest material intensity and is most abundant among the CIGS critical elements, it is not likely to be the limiting element in CIGS deployment. Selenium is least abundant and has the highest material intensity among the CIGS materials, but it is also unlikely to be the element that limits CIGS deployment as it currently costs least and is produced in the greatest volume. More importantly, selenium has important byproduction sources that are currently underutilized, suggesting that its production could be substantially increased without significant increases in cost.xxiv Several arguments suggest that indium could be the limiting component in potential large-scale CIGS deployment: (1) the ratio of indium to gallium in CIGS solar cells is roughly four to one (4:1) by weight;66 (2) indium is roughly one one-hundredth (1/100th) as abundant as gallium in the earth’s crust; (3) indium is already recovered with relatively high efficiency from zinc and other metal ores; and (4) demand for indium as a component in indium-tin-oxide (ITO) transparent conducting films for the flat-panel-display industry is high. Efforts are underway to find an Earth-abundant substitute for ITO — if successful, these efforts would reduce competition for indium from non-CIGS applications.67,68 In addition, recycling ITO from the existing stock of flat-panel displays would provide a potential source of indium for PV applications.

xxivSelenium is obtained principally as a byproduct of copper production, where it is five to seven times more abundant than tellurium. Selenium is also abundant in coal, especially high-sulfur coal, and is enriched in coal ash by an order of magnitude. A dramatic increase in the price of selenium — which would still be compatible with its use in CIGS solar cells given its current order-of-magnitude lower cost than indium — could stimulate selenium recovery from coal. Selenium’s relative abundance in copper and the potential for selenium recovery from coal make it unlikely that the availability of this element would act as the limiting constraint on large-scale CIGS deployment.
**Alternative Active Materials**

For some of the commercial PV technologies discussed previously, the reductions in material intensity that would be required to enable large-scale deployment may be prohibitive given physical and practical limits on layer thicknesses. For example, thinner films may be unable to absorb sunlight fully, or may facilitate the development of short circuits in large-area devices. Avoiding scarce elements altogether would thus be desirable. Many emerging thin-film PV technologies have lower material requirements than the commercial technologies discussed in this chapter and use only Earth-abundant elements.

Returning to Figure 6.4, a stark contrast arises between material requirements for commercial and emerging thin-film PV technologies. Colloidal quantum dot (QD) PV provides a case in point: to deploy 25 TWp of lead sulfide QD solar cells would require the equivalent of only 23 days of global lead production and 7 hours of global sulfur production. This disparity can be attributed to the use of abundant, high-production-volume primary metals and ultra-thin absorber layers in emerging thin-film technologies. Perovskite, copper zinc tin sulfide (CZTS), organic, and dye-sensitized solar cells (DSSC) employ elements that are similarly produced in abundant quantities.

As discussed in Chapter 2, the potential for emerging thin-film technologies to achieve high power per unit weight and their compatibility with thin, flexible substrates may also reduce BOS commodity material requirements. However, low efficiencies, poor stability, and the current absence of module-scale demonstrations currently limit the economic practicality of these emerging technologies, making them important targets for further research.

**FINDING**

Emerging thin-film technologies (e.g., CZTS, perovskite, DSSC, organic, and QD) are better positioned for ambitious scale-up than commercial thin-film technologies (CdTe and CIGS) in terms of materials availability. However, further research is required to overcome efficiency, stability, and manufacturing limitations before emerging thin-film technologies can be considered suitable for large-scale deployment.

It should be emphasized, however, that no single PV technology is likely to capture 100% of the PV market. Commercial thin-film technologies could avoid critical material constraints and remain commercially viable at a deployment scale of up to hundreds of gigawatts by 2050. Furthermore, emerging thin films have not reached the manufacturing scale needed to permit accurate estimation of materials use, materials utilization yield, and manufacturing yield in high-volume module production.
Materials scaling considerations may be a deciding factor in determining which specific PV technologies fulfill the majority of PV demand in the coming decades.

6.5 CONCLUSION

The production of commodity materials used in the fabrication of PV modules and the availability of suitable land area for PV installations are unlikely to be limiting factors in the scaling of PV deployment. However, materials scaling considerations may be a deciding factor in determining which specific PV technologies fulfill the majority of PV demand in the coming decades. If the use of silver for electrical contacts can be reduced or eliminated, silicon PV faces no fundamental materials supply constraints in terms of its ability to meet a large fraction of global electricity demand in 2050. Emerging thin-film technologies based on Earth-abundant elements have not yet been demonstrated at module scale with efficiencies and lifetimes high enough to be economically practical; if these challenges can be overcome, materials availability would not pose a significant barrier to scale-up for these technologies. Current commercial thin-film technologies would need to demonstrate dramatic reductions in active material intensity to fulfill a large fraction of electricity demand. Given the optimistic outlook on materials availability for conventional silicon PV technologies, the difficulties inherent in turning the intermittent output of PV installations into a reliable and dispatchable source of electric power are likely to constitute the more important constraint on large-scale PV deployment in the future. These system integration constraints are the focus of the next chapter.

The difficulties inherent in turning the intermittent output of PV installations into a reliable and dispatchable source of electric power are likely to constitute the more important constraint on large-scale PV deployment in the future.
REFERENCES


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