

# Chapter 2 – Photovoltaic Technology

Solar photovoltaics (PV) are the most widely deployed solar electric technology in the world today. Fueled by light, solar cells operate near ambient temperature, with no moving parts, and they enable generation at any scale:

A 10-square-meter ( $m^2$ ) PV array is in theory no less efficient per unit area than a 10-square-kilometer ( $km^2$ ) array. This contrasts with other generation pathways, such as thermal generators or wind turbines, which lose efficiency with reduced scale.

This chapter reviews current PV technologies and identifies key strengths and remaining technical challenges associated with each.<sup>i</sup> Subsequent sections explore current application areas for PV modules and define the performance metrics that can be expected to drive deployment for each application. From these metrics, three primary technological trends can be identified that will be crucial for enabling large-scale PV deployment in any application area: higher power conversion efficiencies, lower materials usage, and reduced manufacturing complexity and cost.

## 2.1 BASICS OF SOLAR PV ENERGY CONVERSION

A solar PV array consists of one or more electrically connected PV modules — each containing many individual solar cells — integrated with balance-of-system (BOS) hardware components, such as combiner boxes, inverters, transformers, racking, wiring, disconnects, and enclosures. Figure 2.1 shows a complete solar PV system along with cross sections of a module and a cell. In a grid-connected system, combiners, inverters, and transformers convert the low-voltage direct current (dc) output of many individual PV modules into high-voltage

alternating current (ac) power that is fed into the grid. Many off-grid systems also employ charge controllers and batteries to store energy during the day and provide on-demand power during the night. Since current BOS costs typically vary with application but not with PV technology, we refer the reader to the literature on hardware<sup>2</sup> and non-hardware “soft” BOS costs.<sup>3</sup>

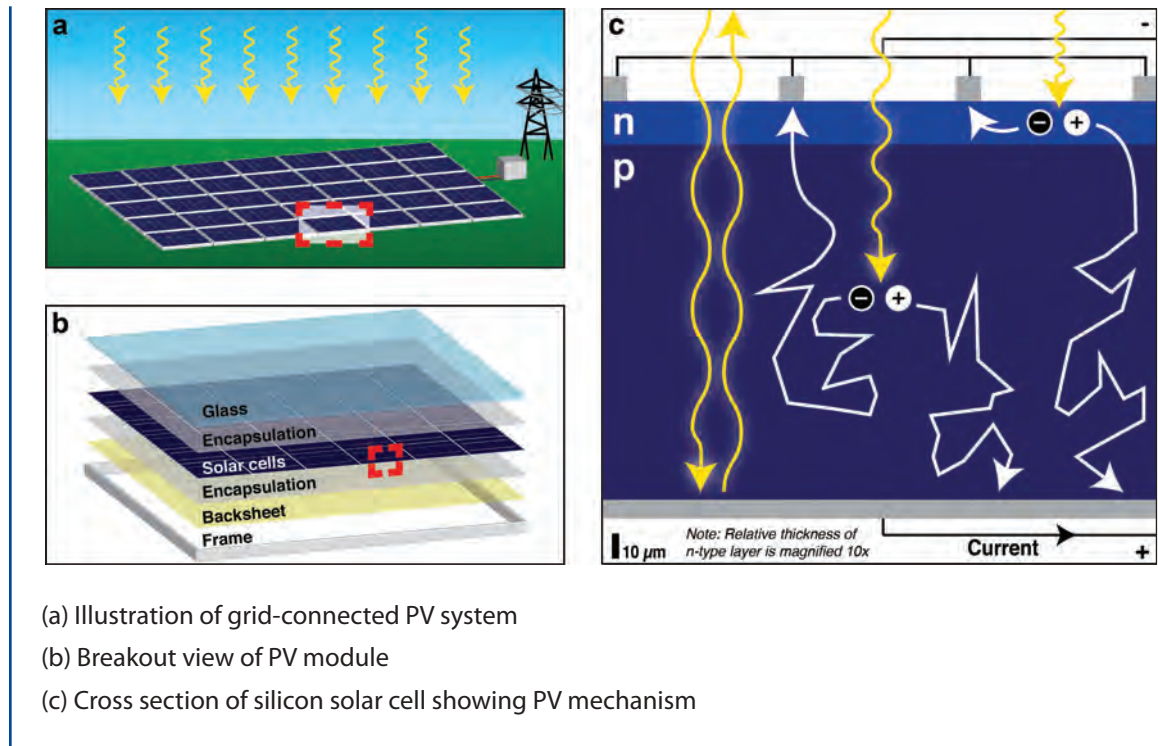
*Solar photovoltaics are the most widely deployed solar electric technology in the world today.*

A typical silicon (Si) PV module consists of a glass sheet for mechanical support and protection, laminated encapsulation layers of ethylene vinyl acetate (EVA) for ultraviolet (UV) and moisture protection; 60 to 96 individual 6-inch-square (15-cm-square) solar cells, each capable of producing 4–5 watts under peak illumination ( $W_p$ ); a fluoropolymer backsheets for further environmental protection; and an aluminum frame for mounting. Common module dimensions are 1 meter by 1.5 meters by 4 centimeters, and peak power ratings range from 260 W to 320 W.

During operation, the front surface of the PV module is illuminated by sunlight. Solar photons are transmitted into each cell, and those photons with sufficiently high energy (i.e., higher than the material-dependent energy bandgap) are absorbed. An absorbed photon transfers its energy to an electron and its positively charged counterpart (a hole). An internal electric field pulls electrons toward one electrode and holes toward the other, resulting in a dc electric current. See Appendix B for a more detailed discussion of the PV conversion process.

<sup>i</sup>The analyses in this chapter are discussed in detail in a recent publication by members of the study group.<sup>1</sup>

**Figure 2.1 Solar PV Energy Conversion**



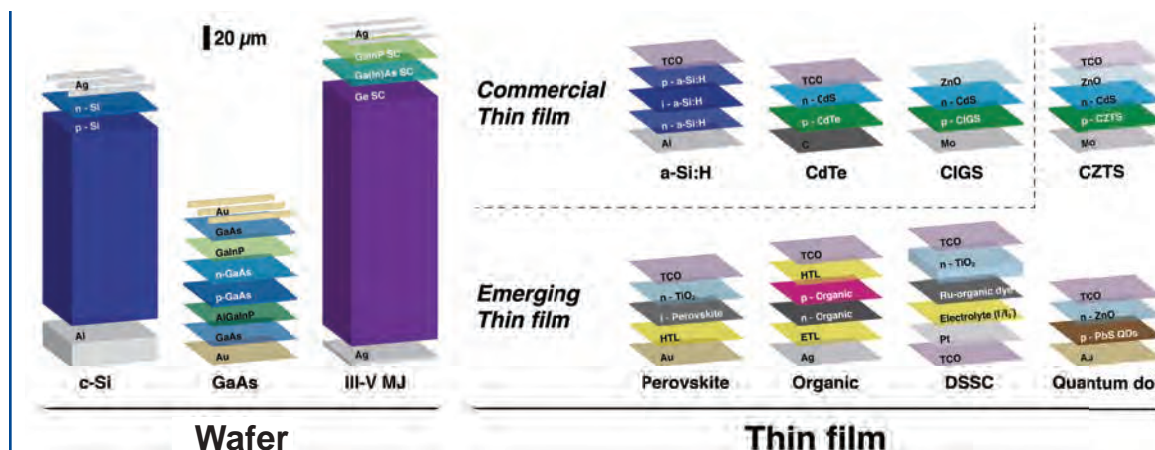
## 2.2 PV TECHNOLOGY OPTIONS

Solar cell technologies are typically named according to their primary light-absorbing material. As shown in Figure 2.2, PV cells can be classified as either wafer-based or thin film. Wafer-based cells are fabricated on semiconducting wafers and can be handled without an additional substrate, although modules are typically covered with glass for mechanical stability and protection. Thin-film cells consist of layers of semiconducting material deposited onto an insulating substrate, such as glass or flexible plastic. The thin-film PV category can be further divided into commercial and emerging thin-film technologies. A more nuanced PV classification scheme is presented in the next section.

The vast majority of commercial PV module production has been — and remains — silicon-based, for reasons that are both technical and historical. Silicon can be manufactured into non-toxic, efficient, and extremely reliable solar cells, leveraging the cumulative learning of more than 60 years of semiconductor processing for integrated circuits. Crystalline silicon (c-Si) solar cells are divided into two categories: single-crystalline (sc-Si) and multicrystalline (mc-Si). The higher crystal quality in sc-Si cells improves charge extraction and power conversion efficiencies, but requires more expensive wafers (by 20% to 30%<sup>4</sup>). A key disadvantage of

*Present crystalline silicon technologies could achieve terawatt-scale deployment by 2050 without major technological advances.*

**Figure 2.2 Current Solar PV Device Structures**



Note: PV device structures are divided into wafer-based and thin-film technologies. Primary light-absorbing layers are labeled in white. Crystalline silicon (c-Si) encompasses single-crystalline and multicrystalline technologies. Modern gallium arsenide (GaAs) cells use thin absorbing films but require wafers as templates for crystal growth. For III-V multijunctions, sub-cells are shown for the industry-standard GaInP/Ga(In)As/Ge triple-junction cell, and some interface layers are omitted for simplicity. A representative single-junction amorphous silicon (a-Si:H) PV structure is shown here, although the a-Si:H PV performance parameters used elsewhere in this chapter correspond to an a-Si:H/nc-Si:H/nc-Si:H triple-junction cell. Front contact grids are omitted for thin-film technologies since the metals used for those grids do not directly contact the active layers and are thus more fungible than those used for wafer-based technologies. Layer thicknesses are shown to scale.

c-Si is its relatively poor ability to absorb light, which encourages the use of thick and brittle wafers. This shortcoming translates to high capital costs, low power-to-weight ratios, and constraints on module flexibility and design. Despite these limitations, c-Si will remain the leading deployed PV technology in the near future, and present c-Si technologies could achieve terawatt-scale deployment by 2050 without major technological advances. Current innovation opportunities include increasing commercial module efficiencies,

reducing manufacturing complexity and costs, reducing the amount of silicon used per watt, and reducing reliance on silver for contact metallization. Materials scarcity limitations for c-Si and other technologies are discussed further in Section 2.5 and in Chapter 6.

**FINDING**

**Crystalline silicon dominates today's PV landscape and will continue to be the leading deployed PV technology for at least the next decade.**

Solar cells based on thin films of c-Si can potentially bypass key limitations of conventional wafer-based c-Si PV while retaining silicon's many advantages and leveraging existing manufacturing infrastructure (see discussion in Box 2.1). Like commercial thin-film technologies, thin-film c-Si PV

can tolerate lower material quality (i.e., smaller grains and higher impurity levels). It uses 10–50 times less material than wafer-based c-Si PV, may enable lightweight and flexible modules, and allows high-throughput processing. However, efficiencies for high-throughput-compatible approaches remain low compared to both wafer-based and leading commercial thin-film technologies, and manufacturing scalability is unproven. The only thin-film c-Si technology that has been commercialized to date was based on c-Si films on glass, but no companies remain in that market today.

*Solar cells based on thin films of crystalline silicon can potentially bypass key limitations of conventional wafer-based cells while retaining silicon's many advantages and leveraging existing manufacturing infrastructure.*

#### **BOX 2.1 WAFER-BASED PV TECHNOLOGIES**

Three primary wafer-based technologies exist today:

- Crystalline silicon (c-Si) solar cells constituted approximately 90% of global module production capacity in 2014<sup>4</sup> and are the most mature of all PV technologies. Silicon solar cells are classified as single-crystalline (sc-Si) or multicrystalline (mc-Si), with respective market shares of approximately 35% and 55% in 2014.<sup>4</sup> Single crystals are typically grown using the Czochralski (CZ) process; the resulting cylindrical ingots are cut into square wafers to increase packing density, resulting in the distinctive truncated-corner sc-Si cell geometry. A high-efficiency variant is the heterojunction with intrinsic thin layer (HIT) architecture, which combines an *n*-type sc-Si wafer with thin amorphous silicon films. These films passivate surface defects and can increase open-circuit voltages by 5%–10%

compared to sc-Si cells.<sup>5,6</sup> Multicrystalline wafers are typically formed by block-casting from liquid silicon and consist of randomly oriented crystalline grains with sizes of around 1 cm<sup>2</sup>. Because grain boundaries hinder charge extraction, their presence in mc-Si cells reduces performance relative to sc-Si cells. Record lab-cell efficiencies stand at 25.6% for sc-Si and 20.4% for mc-Si;<sup>7</sup> record efficiencies for large-area modules are 20.8% for sc-Si and 18.5% for mc-Si.<sup>8</sup> One fundamental limitation of c-Si is its indirect bandgap, which leads to weak light absorption and requires wafers with thicknesses on the order of 100 microns (μm) in the absence of advanced light-trapping strategies. Key technological challenges include stringent material purity requirements, restricted module form factor, and batch-based cell fabrication and module integration processes with relatively low throughput.

## BOX 2.1 WAFER-BASED PV TECHNOLOGIES CONTINUED

- One emerging research direction for c-Si PV is the use of thin (2–50  $\mu\text{m}$ ) c-Si membranes instead of wafers as starting material.<sup>9</sup> Thin films can be produced by thinning of sc-Si wafers,<sup>10,11</sup> epitaxial growth or direct “epi-free” formation on native c-Si substrates with subsequent release and transfer,<sup>12,13,14</sup> and direct deposition on foreign substrates with a seed layer.<sup>12</sup> Wafer thinning strategies can produce extremely thin (<2  $\mu\text{m}$ ) and flexible free-standing silicon layers<sup>10</sup> and have achieved high efficiencies (21.5% with a 47- $\mu\text{m}$ -thick sc-Si wafer<sup>11</sup>), but do not reduce material use or facilitate high-throughput processing. Epitaxial and epi-free transfer approaches have been investigated widely; they allow substrate reuse and can produce high-quality c-Si films and devices with a range of thicknesses (22.3% reported<sup>15</sup> and 21.2% certified cell records<sup>8</sup>). However, epitaxial film growth is relatively slow, and cell areas remain limited to that of conventional wafers. Direct seeded growth on foreign substrates (typically by solid phase crystallization) enables high deposition rates and facilitates monolithic integration of durable modules,<sup>16,17</sup> but the resulting polycrystalline films are generally lower in crystallographic quality, leading to lower efficiencies (11.7% reported<sup>18</sup> and 10.5% certified<sup>8</sup> with c-Si on glass<sup>16</sup>). High-temperature-compatible substrates are also required. Key technical challenges for thin-film c-Si PV include enhancing light absorption by employing advanced anti-reflection and light-trapping strategies, reducing recombination losses by engineering higher-quality crystalline films, reducing processing temperatures to enable flexible substrates and modules without sacrificing material quality, and developing new methods for high-throughput inline module integration.
- Gallium arsenide (GaAs) is a compound semiconductor that is almost perfectly suited for solar energy conversion, with strong absorption, a direct bandgap that is well matched to the solar spectrum, and very low non-radiative energy loss. GaAs has achieved the highest power conversion efficiencies of any material system — 28.8% for lab cells and 24.1% for modules.<sup>7,8</sup> A technique known as epitaxial liftoff creates thin, flexible GaAs films and amortizes substrate costs by reusing GaAs wafers,<sup>19</sup> but has not yet been demonstrated in high-volume manufacturing. Cost-effective production will require low-cost wafer polishing, which defines a cost floor for epitaxial substrates, as well as improved film quality and more substrate reuse cycles.
- III-V multijunction (MJ) solar cells use a stack of two or more single-junction cells with different bandgaps to absorb light efficiently across the solar spectrum by minimizing thermalization (heat) losses. Semiconducting compounds of group III elements (Al, Ga, In) and group V elements (N, P, As, Sb) can form high-quality crystalline films with variable bandgaps, yielding unparalleled record cell and module efficiencies — 46.0% and 36.7%, respectively, under concentrated illumination.<sup>7,8</sup> III-V MJs are the leading technology for space applications, with their high radiation resistance, low temperature sensitivity, and high efficiency. But complex manufacturing processes and high material costs make III-V MJ cells prohibitively expensive for large-area terrestrial applications. Concentrating sunlight reduces the required cell area by replacing cells with mirrors or lenses, but it is still unclear whether concentrating PV systems can compete with commercial single-junction technologies on cost. Current research and development (R&D) efforts are focused on dilute nitride materials (e.g., GaInNAs),<sup>20</sup> lattice-mismatched (metamorphic) approaches,<sup>21</sup> and wafer bonding.<sup>22,23</sup> Key challenges for emerging III-V MJ technologies include improving long-term reliability and large-area uniformity, reducing materials use, and optimizing cell architectures for variable operating conditions.

While c-Si currently dominates the global PV market, alternative technologies may be able to achieve lower costs in the long run. Solar cells based on thin semiconducting films now constitute approximately 10% of global PV module production capacity.<sup>4</sup> Thin-film cells are made by additive fabrication processes,

*While crystalline silicon currently dominates the global PV market, alternative technologies may be able to achieve lower costs in the long run.*

which may reduce material usage, manufacturing capital expenditures, and lifecycle greenhouse gas emissions.<sup>24,25</sup> This category extends from commercial technologies based on conventional inorganic semiconductors (Box 2.3) to emerging technologies based on nanostructured materials (Box 2.4). World-record lab-cell efficiencies for all technologies discussed here are shown in Figure 2.3.

Commercial thin-film PV technologies are represented primarily by cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and hydrogenated amorphous silicon (a-Si:H). These materials absorb light 10–100 times more efficiently than silicon, allowing the use of films just a few microns ( $\mu\text{m}$ ) thick, as shown in Figure 2.4. Their low use of raw materials is thus a key advantage of these technologies. Advanced factories can produce thin-film modules in a highly streamlined and automated fashion, leading to low per-watt module costs.

A key disadvantage of today's commercial thin-film modules is their comparatively low average efficiency, typically in the range of 12%–15%, compared to 15%–21% for c-Si. Reduced efficiencies increase system costs due to area-dependent BOS components. Most thin-film materials today are polycrystalline and contain much higher defect densities than c-Si. Some compound semiconductors (e.g., CIGS) have complex stoichiometry, making high-yield, uniform, large-area deposition a formidable process-engineering challenge. Sensitivity to moisture and oxygen often requires more expensive hermetic encapsulation to ensure 25-year reliability. Recycling of regulated, toxic elements (e.g., cadmium) and reliance on rare elements (e.g., tellurium and indium) can limit the potential for large-scale deployment, as discussed in Chapter 6.

Current innovation opportunities in thin-film technology include improving module efficiency, improving reliability by introducing more robust materials and cell architectures, and decreasing reliance on rare elements by developing new materials with similar ease of processing.

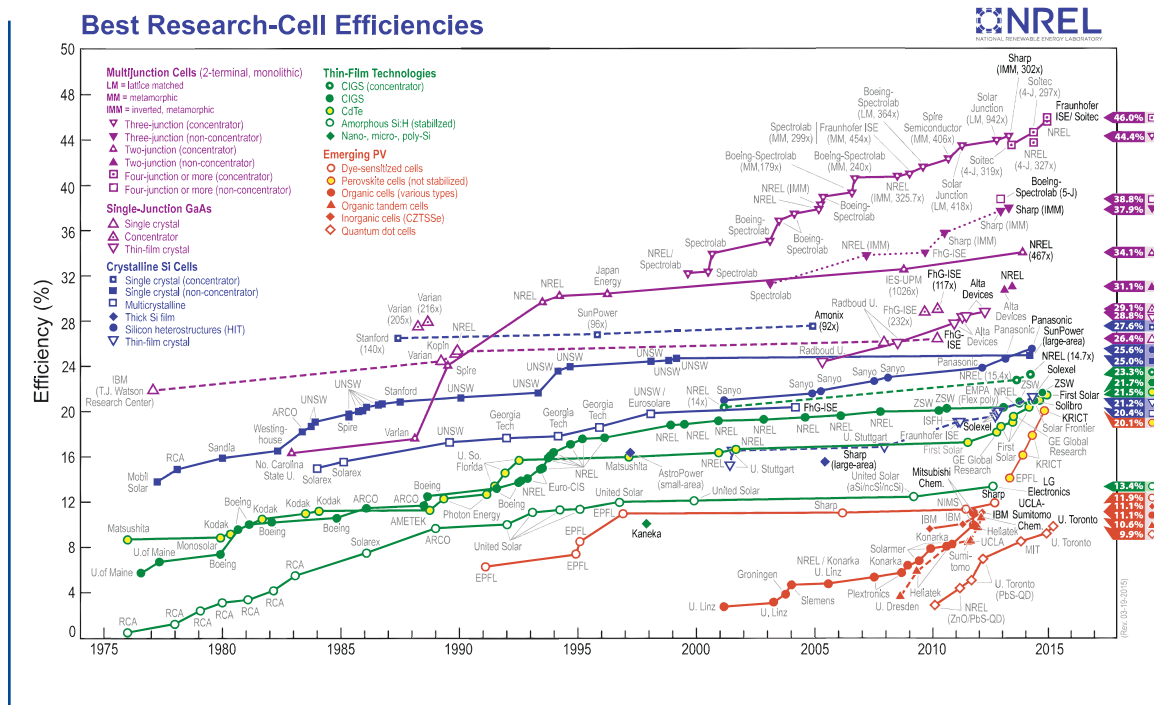
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## FINDING

**Inherent limitations of current silicon technologies, including high processing complexity and silicon's inherently poor light absorption, drive the need for sustained R&D in advanced silicon and alternative technologies.**

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**Figure 2.3 Trends in Record Lab-Cell Power Conversion Efficiencies<sup>7</sup>**



**FINDING**

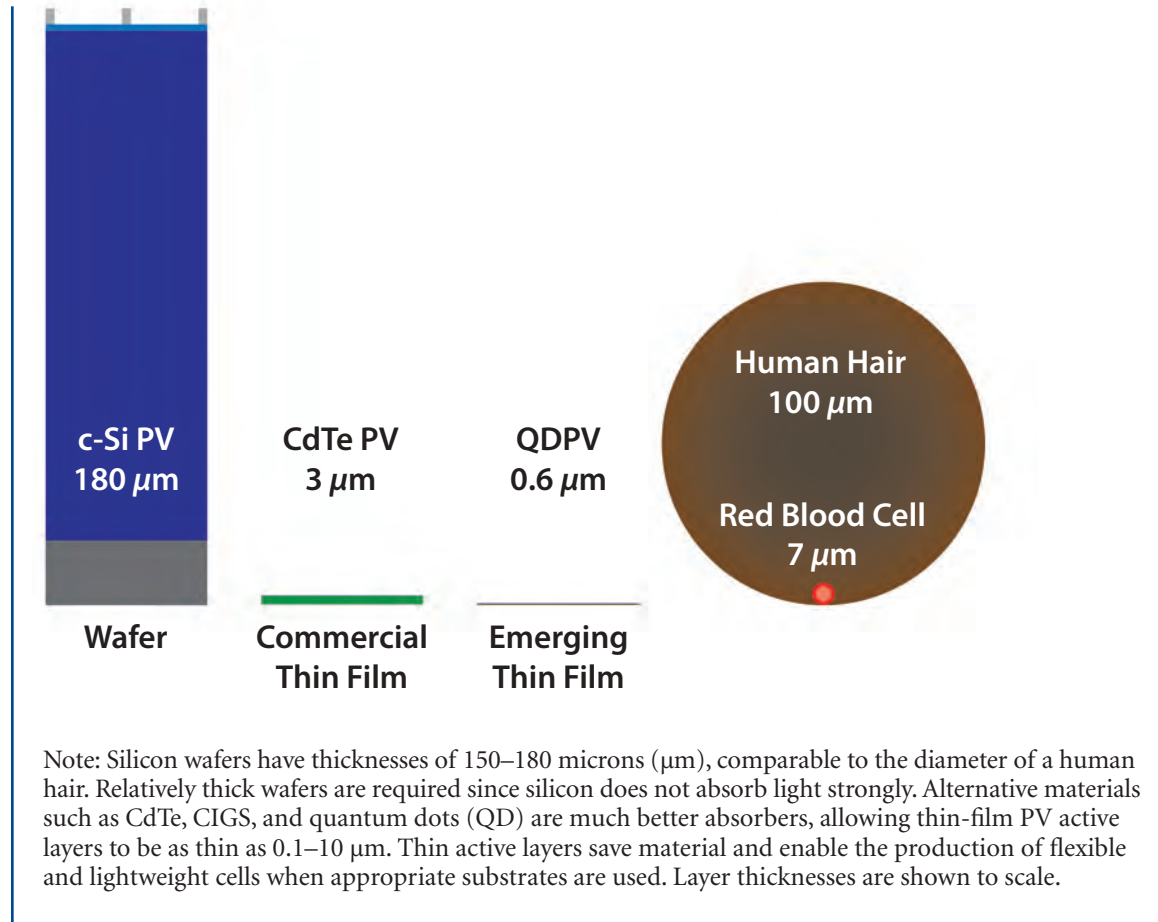
**Commercial thin-film PV technologies compete well on module cost, but their lower efficiencies may increase overall system cost. Furthermore, the reliance of some thin-film technologies on rare and toxic elements may create materials issues that impede their ability to scale.**

In recent years, several new thin-film PV technologies have emerged as a result of intense research and development (R&D) efforts in materials discovery and device engineering. These technologies rely on nanostructured

*New thin-film PV technologies offer potentially unique device-level properties that could open the door to novel applications for solar PV.*

materials, or nanomaterials, which can be rationally engineered to achieve desired optical and electronic properties. While these technologies range in maturity from fundamental materials R&D to early commercialization and have not yet been deployed at large scale, they offer potentially unique device-level properties such as visible transparency, high weight-specific power (watts per gram [W/g]), and novel form factors. These qualities could open the door to novel applications for solar PV.

**Figure 2.4 Solar Cell Thickness by Technology Classification**





## BOX 2.2 COMMERCIAL THIN-FILM PV TECHNOLOGIES

Key commercial thin-film PV technologies include the following:

- Hydrogenated amorphous silicon (a-Si:H) is a non-crystalline form of silicon that offers stronger absorption than crystalline silicon, although its larger bandgap — at 1.5–1.8 electron volts (eV), compared to 1.12 eV for c-Si — reduces the range of wavelengths that can be absorbed. A 300-nanometer (nm) film of a-Si:H can absorb approximately 85% of above-bandgap solar photons in a single pass, enabling the production of lightweight and flexible solar cells. An a-Si:H cell can be combined with cells based on nanocrystalline silicon (nc-Si) or amorphous silicon-germanium (a-SiGe) alloys to form a multijunction (MJ) cell without lattice-matching requirements. Most commercial a-Si:H modules today use MJ cells. Silicon is cheap, abundant, and non-toxic, but while a-Si:H cells are well suited for small-scale and low-power applications, their susceptibility to light-induced degradation (known as the Staebler-Wronski effect<sup>26</sup>) and their low efficiency compared to other mature thin-film technologies (13.4% triple-junction lab record<sup>8</sup>) limit market adoption.
- Cadmium telluride (CdTe) is the leading thin-film PV technology in terms of worldwide installed capacity. CdTe is a favorable semiconductor for solar energy harvesting, with strong absorption across the solar spectrum and a direct bandgap of 1.45 eV. Record efficiencies of 21.0% for lab cells and 17.5%

for modules are among the highest for thin-film solar cells, and commercial module efficiencies continue to improve steadily.<sup>7,8</sup> CdTe technologies employ high-throughput manufacturing processes and offer the lowest module costs of any PV technology on the market today, although relatively high processing temperatures are required (~500°C). Concerns about the toxicity of elemental cadmium (Cd)<sup>27</sup> and the scarcity of tellurium (Te) (see Chapter 6) have motivated research on alternative material systems that exhibit similar ease of manufacturing but rely on abundant and non-toxic elements.

- Copper indium gallium diselenide ( $\text{CuIn}_x\text{Ga}_{1-x}\text{Se}_2$ , or CIGS) is a compound semiconductor with a direct bandgap of 1.1–1.2 eV. Like CdTe, CIGS films can be deposited by a variety of solution- and vapor-based techniques on flexible metal or polyimide substrates, favorable for building-integrated and other unconventional PV applications. CIGS solar cells exhibit high radiation resistance, a necessary property for space applications. Record efficiencies stand at 21.7% for lab cells and 15.7% for modules.<sup>7,8</sup> Key technological challenges include high variability in film stoichiometry and properties, limited understanding of the role of grain boundaries, low open-circuit voltage due to material defects, and the engineering of higher-bandgap alloys to enable MJ devices. Scarcity of elemental indium (In) (see Chapter 6) could hinder large-scale deployment of CIGS technologies.

### BOX 2.3 EMERGING THIN-FILM PV TECHNOLOGIES

Key emerging thin-film PV technologies include the following:

- Copper zinc tin sulfide ( $\text{Cu}_2\text{ZnSnS}_4$ , or CZTS) is an Earth-abundant alternative to CIGS, with similar processing strategies and challenges. One key challenge involves managing a class of defects known as cation disorder — uncontrolled inter-substitution of copper (Cu) and zinc (Zn) cations creates point defects that can hinder charge extraction and reduce the open-circuit voltage. Certified record lab-cell efficiencies have reached 12.6%.<sup>8,28</sup>
- Perovskite solar cells recently evolved from solid-state dye-sensitized cells,<sup>29,30</sup> and have quickly become one of the most promising emerging thin-film PV technologies, with leading efficiencies advancing from 10.9% to 20.1% in less than three years of development.<sup>7,31,32</sup> The term “perovskite” refers to the crystal structure of the light-absorbing film, and the most widely investigated perovskite material is the hybrid organic-inorganic lead halide  $\text{CH}_3\text{NH}_3\text{PbI}_{3-x}\text{Cl}_x$ . Polycrystalline films can be formed at low temperatures by solution or vapor deposition.<sup>31,33</sup> Key advantages of this class of material include long charge carrier diffusion lengths, low recombination losses, low materials cost, and the potential for bandgap tuning by cation or anion substitution. Early perovskite devices have achieved impressively high open-circuit voltages (about 1.1 V), typically the most difficult solar cell performance parameter to improve. Key technological challenges include the refined control of film morphology and material properties, high sensitivity to moisture, unproven cell stability, and the use of toxic lead.
- Organic photovoltaics (OPV) use organic small molecules or polymers to absorb incident light. These materials consist mostly of Earth-abundant elements and can be assembled into thin films by low-cost deposition methods, such as inkjet printing and thermal evaporation. Organic multijunction (MJ) cells may be much easier to fabricate than conventional MJ cells because of their high defect tolerance and ease of deposition. Small-molecule and polymer OPV technologies have recently reached 11.1% efficiencies in the lab,<sup>7</sup> but large-area cell and module efficiencies remain much lower. Key concerns involve inefficient transport of excited electron-hole pairs and charge carriers, low large-area deposition yield, poor long-term stability under illumination, and comparatively low ultimate efficiency limits.
- Dye-sensitized solar cell (DSSC) technology is among the most mature and well understood of nanomaterial-based PV options. These photoelectrochemical cells consist of a transparent inorganic scaffold (typically a nanoporous titanium dioxide film) sensitized with light-absorbing organic dye molecules (usually ruthenium complexes). Unlike the other technologies discussed here, which rely on solid-state semiconductors to transport electrons and generate a photocurrent, DSSCs often use a liquid electrolyte to transport ions to a platinum counter electrode. DSSCs have achieved efficiencies of up to 12.3%<sup>34</sup> (11.9% certified<sup>7</sup>) and may benefit from low-cost materials, simple assembly, and the possibility of flexible modules. Key challenges involve limited long-term stability under illumination and high temperatures, low absorption in the near-infrared, and low open-circuit voltages caused by interfacial recombination.
- Colloidal quantum dot photovoltaics (QDPV) use solution-processed nanocrystals, also known as quantum dots (QD), to absorb light. The ability to tune the absorption spectrum of colloidal metal chalcogenide nanocrystals, primarily lead sulfide (PbS), allows efficient harvesting of near-infrared photons, as well as the potential for MJ cells using a single material system. QDPV technologies are improving consistently, with a record lab-cell efficiency of 9.2%,<sup>7</sup> and they offer promising ease of fabrication and air-stable operation. Key challenges include incomplete understanding of QD surface chemistry, low charge carrier mobility, and low open-circuit voltages that may be limited fundamentally by mid-gap states or inherent disorder in QD films.

### 2.3 PV TECHNOLOGY CLASSIFICATION BY MATERIAL COMPLEXITY

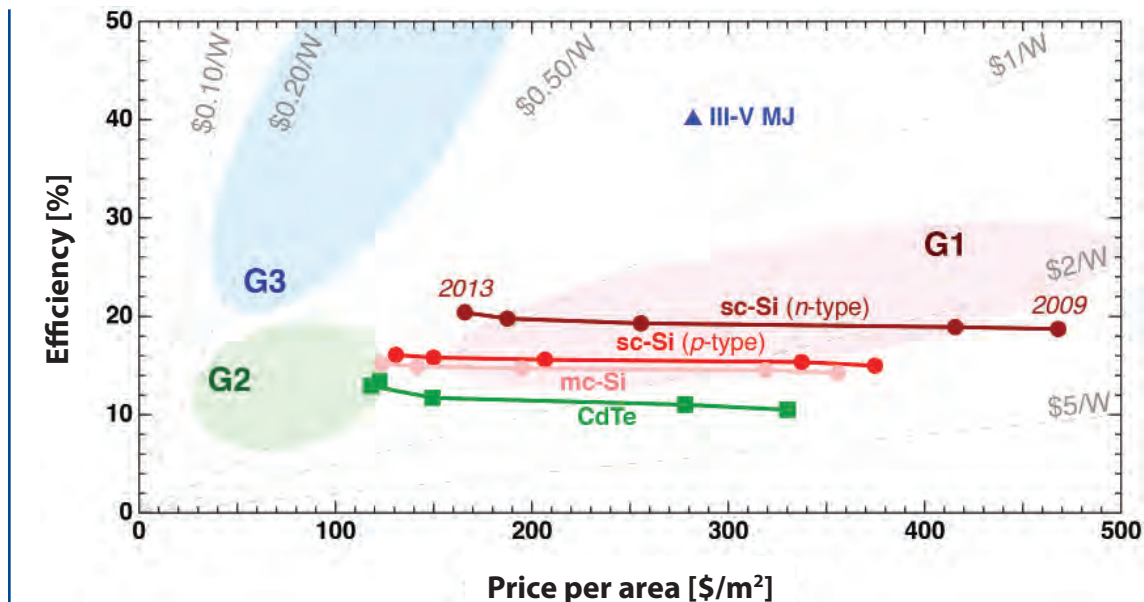
Solar PV technologies can be ranked by power conversion efficiency, module cost, material abundance, or any other performance metric. The next section discusses several important application-specific metrics. The most widely used classification scheme today relies on two metrics, module efficiency and area cost, that delineate three distinct generations.<sup>35,36</sup>

1. First generation (G1) technologies consist of wafer-based cells of c-Si and GaAs.
2. Second generation (G2) technologies consist of thin-film cells, including a-Si:H, CdTe, and CIGS.

3. Third generation (G3) technologies include novel thin-film devices, such as dye-sensitized, organic, and quantum dot (QD) solar cells, along with a variety of “exotic” concepts and strategies, including spectral-splitting devices (e.g., MJ cells), hot-carrier collection, carrier multiplication, and thermophotovoltaics.<sup>35</sup>

This generational scheme may not adequately describe the modern PV technology landscape. Many new technologies like QD and perovskite solar cells resist classification, yet have largely been lumped together under the G3 label of “advanced thin films.”<sup>36</sup> Any chronological classification scheme is likely to treat older technologies pejoratively, in favor of new “next-generation” concepts. Yet silicon and commercial thin-film technologies, such as CdTe, far outperform emerging thin-film technologies.

**Figure 2.5 Limited Utility of Generational Classification Scheme**



Note: The figure plots trends in module efficiency<sup>37</sup> and price per area (derived from pvXchange module price indices<sup>38</sup>) over the period from 2009 to 2013. Trends are shown for commercial PV technologies in three conventional generations (G1 in red, G2 in green, and G3 in blue). Current G1 and G2 modules cluster near the region originally defined as G2, limiting the usefulness of this representation. The single G3 data point corresponds to performance projections for a III-V MJ module.<sup>23</sup>

The three generations are commonly represented as shaded regions on a plot of module efficiency vs. area cost. Figure 2.5 shows these regions as originally defined in 2001,<sup>35,iii</sup> along with module performance trends for commercial PV technologies from 2009 to 2013. All technologies move toward the upper-left corner with time as efficiencies rise and costs fall. Although historical G1 and G2 price and performance data fall roughly in the stated zones, current modules do not obey this delineation. Nearly all current G1 (c-Si) and G2 (CdTe) technologies appear close to the zone designated G2. Furthermore, no G3 technology to our knowledge has reached the zone marked G3. More generally, we find that average commercial module prices for both G1 and G2 technologies tend to cluster along a single  $\$/W_p$  line in any given year, likely due to competitive market dynamics.

*The repeating units that constitute the active material in modern PV technologies run the gamut in complexity from single silicon atoms to quantum dots that contain thousands of lead and sulfur atoms.*

This report advocates an alternative approach to PV technology classification that is based on material complexity. Material complexity can be defined roughly as the number of atoms in a unit cell, molecule, or other repeating unit.<sup>iii</sup> The repeating units that constitute the active material in modern PV technologies run the gamut in complexity from single silicon atoms

to quantum dots that contain thousands of lead and sulfur atoms.

In this framework, all PV technologies fall on a spectrum from elemental (lowest) to nano-material (highest) complexity, as shown in Figure 2.6. At one end of the material complexity spectrum are wafer-based technologies with relatively simple building blocks, including c-Si and III-V cells. Technologies based on more complex materials fall under the broad umbrella of thin-film solar cells, ranging from polycrystalline thin films, such as CdTe and CIGS, to complex nanomaterials such as organics and QDs.

Material complexity is not equivalent to processing complexity. In fact, one type of complexity can often be traded off for the other: Silicon may be considered a simple material, but processing silicon is a complex industrial procedure, due to relatively stringent purity requirements for solar-grade material.<sup>iv</sup> More complex materials typically employ solution-based synthetic procedures. Once synthesized, they can be deposited as thin films quickly and easily, without expensive equipment or high-temperature processing.

It is also important to note that higher material complexity is not always better. Technological maturity and cell efficiencies tend to vary inversely with complexity. In the history of semiconductor technology, crystalline materials based on elemental and compound building

<sup>ii</sup>The generations shown in Figure 2.5 are typically represented in terms of cost per area, rather than price per area. Here we use module prices because manufacturing cost data are not consistently available. However, we must emphasize that price is an imperfect proxy for underlying costs. Thus, reductions in module price may not reflect technological progress.

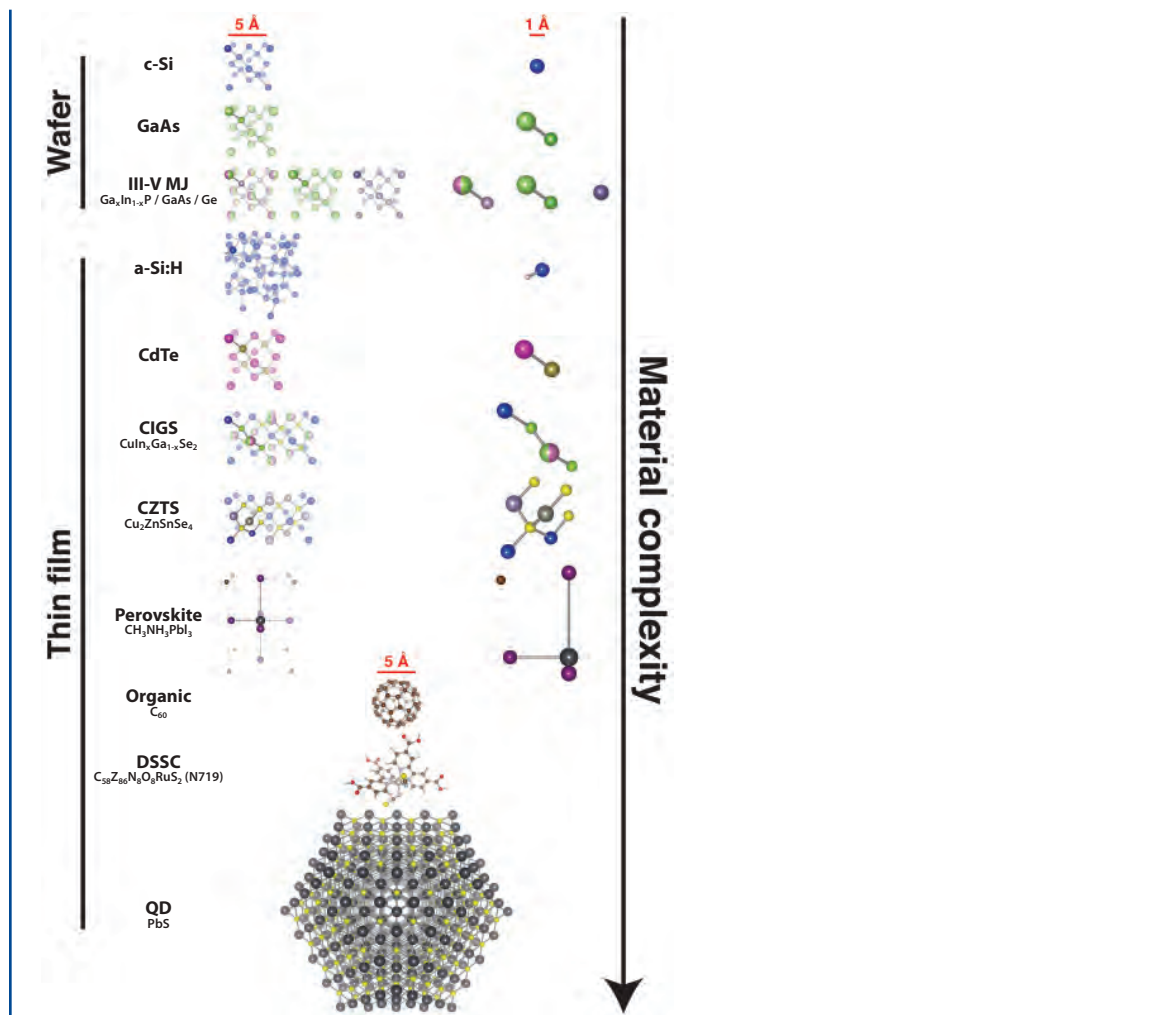
<sup>iii</sup>Material complexity is associated with the degree of disorder in a material. Amorphous materials can be qualitatively classified as generally more complex than their crystalline counterparts, since relative atomic positions are well defined in crystals, less defined in polycrystalline films, and not at all defined in amorphous films.

<sup>iv</sup>Solar-grade silicon (SG-Si) is typically refined to a purity of “six nines” (99.9999%). Integrated circuit (IC) manufacturing requires a silicon purity of “nine nines” (99.9999999%). For comparison, materials used in organic solar cells and other emerging thin-film technologies often have purities on the order of 99%. Less-stringent purity requirements often reduce processing complexity and cost.

blocks were discovered, studied, and engineered first, for electronic and optoelectronic devices alike. The first solar cell, made in 1883 by Charles Fritts, was based on a wafer of selenium. Less complex materials like silicon are better understood than novel nanomaterials; improved control over electronic and optical

properties allows better device modeling and engineering. C-Si and conventional III-V semiconductors have achieved the highest efficiencies among PV technologies, and silicon now commands by far the largest share of the global market.

**Figure 2.6 Alternative PV Technology Classification Scheme Based on Material Complexity**



Note: Crystal unit cells or molecular structures of representative materials are shown for each technology, with crystal bases highlighted and expanded (right column) to illustrate the relative complexity of different material systems. Lattice constants and bond lengths are shown to scale, while atomic radii are 40% of actual values. Scale bars are in angstroms (1 Å = 0.1 nm = 10<sup>-10</sup> meter). Wafer-based materials consist of single- or few-atom building blocks. Thin-film materials range from amorphous elemental materials (a-Si:H) to complex nanomaterials with building blocks containing up to thousands of atoms (e.g., PbS QDs). Single carbon atoms (brown) in the perovskite crystal structure represent methylammonium (CH<sub>3</sub>NH<sub>3</sub>) cations.

*Increased material complexity gives rise to several novel and potentially valuable technological attributes.*

On the other hand, increased material complexity also gives rise to several novel and potentially valuable technological attributes:

**Reduced materials use** – Absorber thicknesses tend to decrease with increasing complexity, since complex building blocks are often engineered or selected for maximum light absorption. Strong absorption in nanomaterials reduces material use and cell weight.

**Flexible substrates and versatile form factors** – Commercial thin-film PV technologies are characterized by one-step formation of the absorber material on a substrate, while emerging thin films often employ separate active material synthesis and deposition steps. Synthesizing building blocks such as organic molecules and QDs in a separate chemical reaction at high temperatures allows them to be deposited at low temperatures. Flexible and lightweight plastic substrates can then be used, potentially enabling high weight-specific power.

**Visible transparency** – The lack of long-range crystalline order in organic molecules leads to light absorption that does not strictly increase with photon energy. Non-monotonic absorption allows some organic materials to absorb infrared radiation while transmitting visible light, potentially enabling the development of visibly transparent solar cells.

**Defect tolerance** – Complex nanomaterials may tolerate defects and impurities more readily than single-crystalline and polycrystalline materials.

Since future solar cell applications may well require some or all of these performance characteristics, improving the conversion efficiency and stability of promising complex material platforms is a key priority for technology innovation.

## 2.4 PERFORMANCE METRICS FOR FUTURE PV APPLICATIONS

To understand the technical challenges for PV adoption and scale-up, it is instructive to define performance metrics that can be used to compare candidate PV technologies. These metrics can be purely technical or may incorporate both technical and economic factors. This section considers key performance metrics that will drive PV adoption in two primary classes of applications: grid connected and off grid.

Grid-connected applications, including those at the residential, commercial, and utility scale, involve ground- or roof-mounted PV arrays with peak power outputs ranging from a few kilowatts to hundreds of megawatts. Grid connectivity imposes a single dominant

*Grid connectivity imposes a single dominant requirement: low levelized cost of electricity.*

requirement: low levelized cost of electricity (LCOE, in \$/kWh). A comparison of LCOE for solar PV and for competing generation sources dictates the economic feasibility of a grid-connected PV system, although it is worth emphasizing that LCOE alone may underestimate the value of solar generation due to temporal variation in electricity demand and price (see Chapter 5 and Schmalensee<sup>39</sup>). Other important metrics include system cost (\$/W<sub>p</sub>), energy yield (kWh/W<sub>p</sub>), reliability, and — where roof loading is crucial — specific power. Most of these metrics also directly affect LCOE.

Off-grid applications for PV technology, including applications to power portable devices and for deployment in developing countries, tend to value system cost along with a variety of non-cost factors, such as specific power, form factor (e.g., flexibility), aesthetics, and durability. One leading example is the use of small-area solar cells to power mobile phones and other portable electronic devices. In many applications, significant value may derive from low module weight, making specific power an important metric. It should be noted that PV technologies with efficiencies too low to power the developed world's high-power mobile devices are often adequate for the developing world's low-power mobile needs.

*PV technologies with efficiencies too low to power the developed world's high-power mobile devices are often adequate for the developing world's low-power mobile needs.*

Another potential off-grid application is building-integrated PV (BIPV), in which PV modules are used in structural features that are not primarily associated with electricity production (e.g., windows, skylights, shingles, tiles, curtains, and canopies). Aesthetic concerns often drive module form factor and positioning, which may be sub-optimal for solar energy collection. That said, some BIPV systems may achieve competitive LCOE by piggybacking on the materials, installation, and maintenance costs of the existing building envelope. Other areas for potential PV applications are discussed in Box 2.4.

#### **BOX 2.4 UNIQUE PV APPLICATIONS**

The technical demands of diverse applications continue to drive major foundational R&D efforts toward the development of alternative PV technologies. So-called "next-gen" technologies can be classified according to their purpose:

- Ultra-high efficiency – Some applications (e.g., satellites and defense applications) require power conversion efficiencies over 30%, twice the efficiency of typical commercial modules. Achieving such high efficiencies often requires more expensive approaches involving multiple absorber materials (e.g., multijunction (MJ) and spectral-splitting devices) or concentration of sunlight. Most recently, considerable effort has been dedicated to combining c-Si technology with an overlayer of wide-bandgap thin-film material, such as III-Vs, chalcogenides, metal oxides, or perovskites.

- Unique form factors – Some applications may benefit from form factors that depart from traditional glass-covered modules. Examples include BIPV, portable consumer devices, and solar textiles. Flexible solar cells and novel three-dimensional architectures may facilitate the ubiquitous deployment of PV technologies.
- Unique aesthetics – Colored or transparent solar cells, which absorb infrared or ultraviolet light, may be considered to have aesthetic advantages when incorporated into certain applications, including construction façades, windows, and consumer electronics.

## 2.5 PV TECHNOLOGY TRENDS

The performance metrics described above reflect application-specific performance demands. The extent to which these needs are fulfilled by any particular PV technology will determine the commercial viability of that technology. These metrics translate to three technologically relevant characteristics that will be shared by most future PV technologies and that can help guide future technology development. We expect technologies exhibiting these characteristics to be deployed in a wide variety of applications.

*No single PV technology today excels in all three key technical characteristics: high power conversion efficiency, low materials usage, and low manufacturing complexity and cost.*

### 1. High power conversion efficiency

(% or  $W/m^2$ ) – We expect to see continuous but incremental progress toward higher efficiencies as technologies improve. Increasing sunlight-to-electricity conversion efficiency directly benefits most of the metrics discussed earlier. However, gains in efficiency at the module level often result from sustained investment in R&D, capital equipment, and increasingly complex manufacturing processes. Thus it is reasonable to anticipate a gradual trend toward higher efficiencies over many years, rather than a sudden quantum leap in performance.

### 2. Low materials usage ( $g/m^2$ or $g/W$ ) –

We expect a trend toward lower materials usage for all technologies. Thinner glass, frames, and active layers can reduce material consumption and cost, and increase specific power and cell flexibility. In addition, PV technologies that require scarce elements may be unable to achieve terawatt-scale deployment (see Chapter 6). Materials use and elemental abundance for different technologies are shown in Figure 2.7.

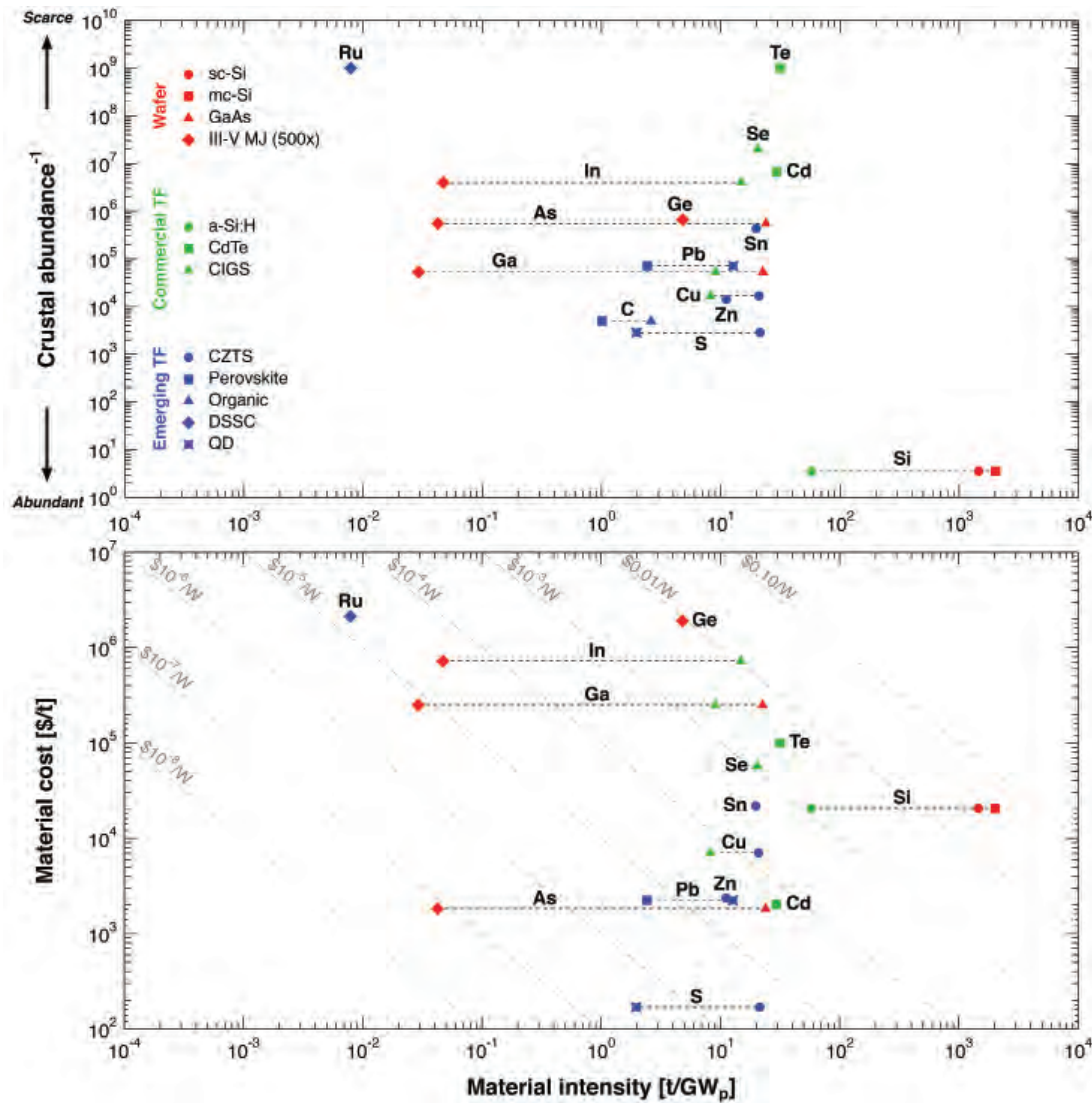
### 3. Low manufacturing complexity and cost –

High capital equipment expenditures for manufacturing plants may be a bottleneck for large-scale PV deployment. In any case, there is a premium on low upfront equipment cost. For both c-Si and alternative technologies, streamlined manufacturing approaches could simultaneously reduce upfront cost and enable new form factors. Both should therefore be prioritized in R&D efforts. Examples include flexible solar cells printed by low-cost methods using CIGS, QD, or organic inks, though we note that the latter two types have not yet been demonstrated at scale. Key technical challenges for such approaches typically involve module reliability, manufacturing yield, and efficiency.

No single PV technology today excels in all three technical characteristics listed above. Figure 2.8 compares the technological maturity, power conversion efficiency, materials use, and specific power of today's PV technologies. Such comparisons point to several general observations: (1) C-Si and conventional thin films are the only technologies deployed at large scale today. (2) Record efficiencies for large-area modules lag behind those of lab cells by a significant margin, as discussed in Box 2.5. (3) Thin-film PV technologies use 10 to 1000 times less material than c-Si, reducing cell weight per unit area and increasing power output per unit weight. (4) All PV technologies deployed today have been under development for at least three decades.

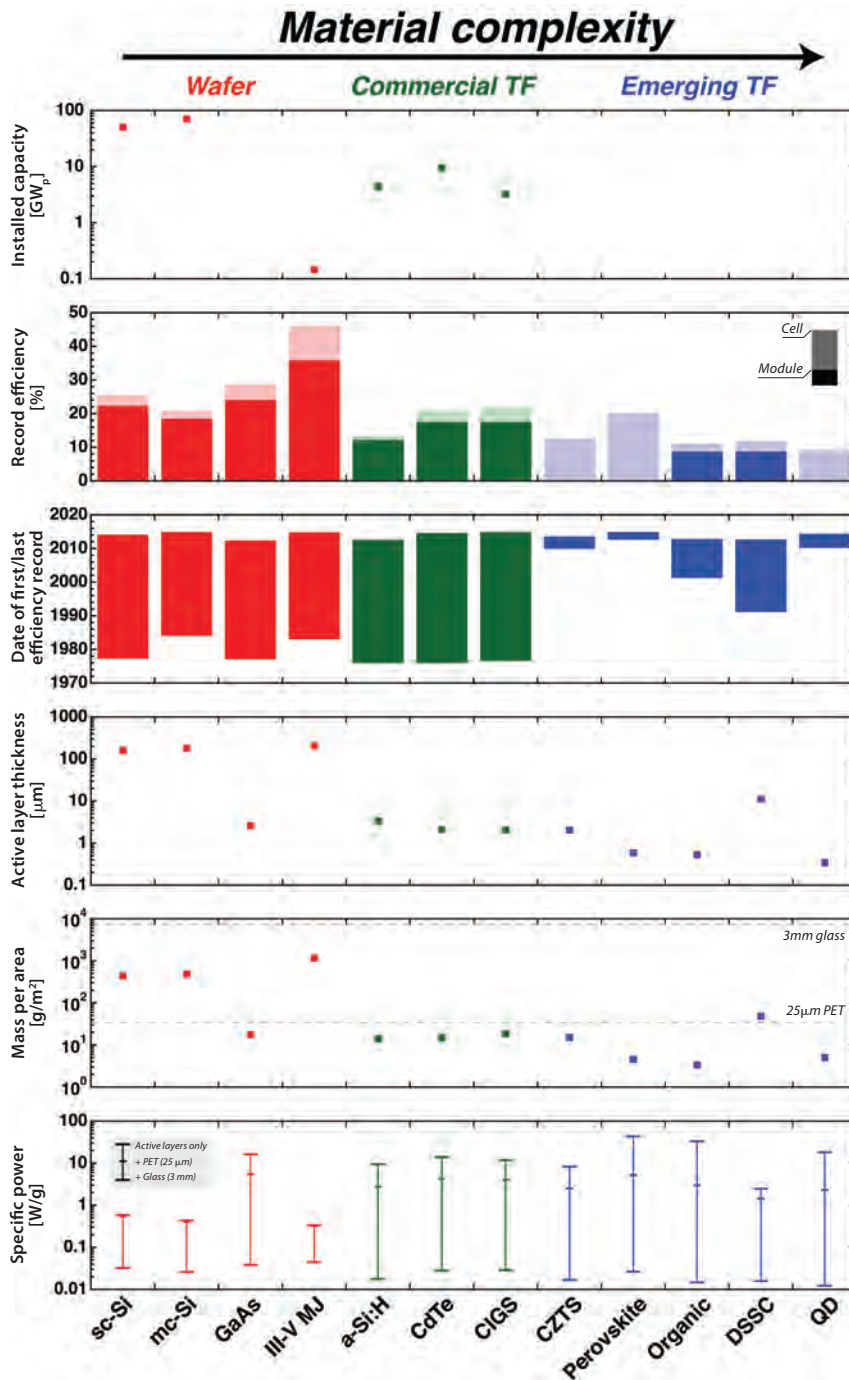


**Figure 2.7 Materials Usage, Abundance, and Cost for Key Elements Used in Commercial and Emerging PV Technologies**



Note: Material intensities are calculated using typical device structures and absorber compositions, assuming 100% material utilization and manufacturing yield, and current record lab-cell efficiencies.<sup>7</sup> Each element has an estimated crustal abundance<sup>40</sup> and market price and thus a fixed position along the y-axis, but varies in position along the x-axis depending on technology-specific material needs. Technologies that tend toward the lower left corner of each plot can achieve large-scale deployment with lower risk of raw material cost and availability limitations. In the bottom plot, gray dashed lines indicate the contribution of raw material costs to the total cell cost in  $\$/W_p$ , assuming current market prices. Material intensities are calculated for III-V MJs based on the standard triple-junction cell described earlier, for a-Si:H based on an a-Si:H/nc Si:H/nc Si:H triple-junction, for organic cells based on a tandem polymer device structure, for perovskite cells based on the mixed-halide perovskite  $CH_3NH_3PbI_2Cl$ , and for DSSCs based on the common N719 dye. A concentration ratio of 500x is assumed for III-V MJs.

**Figure 2.8 Key Metrics for Photovoltaic Technologies Ordered by Material Complexity**



Note: Metrics are current at the time of this writing and include cumulative global installed capacity,<sup>41,42</sup> power conversion efficiency under 1 sun (except III-V MJ), time elapsed since first certified by the National Renewable Energy Laboratory (NREL),<sup>7</sup> absorber thickness, and cell mass per area. All of these metrics generally decrease with increasing material complexity. Specific power is shown for active layers alone and for cells with a substrate or encapsulation layer made of 25-μm polyethylene terephthalate (PET) or 3-mm glass. Despite their lower efficiencies, thin-film cells on thin and flexible substrates can achieve much higher specific power than wafer-based cells. All metrics are calculated based on record efficiency or representative device structures. Record lab-cell efficiencies are assumed in specific power calculations. A concentration ratio of 500x is assumed for III-V MJs unless otherwise specified.

Today's emerging technologies are improving far faster than current deployed technologies improved in their early stages, but it is important to note that the road to market and large-scale deployment is invariably long.

*It is clear that innovation opportunities exist for all PV technologies.*

Practical limits to PV deployment will depend on a wide range of technological and economic factors, as discussed in Chapter 6. While the goal need not be a “silver-bullet” technology — different applications may call for different solutions — it is clear that innovation opportunities exist for all PV technologies.

#### **BOX 2.5 MODULE VS. CELL EFFICIENCY**

Commercial PV modules can be up to 40% less efficient than small-area lab cells. Two primary types of losses — intrinsic and extrinsic — occur in the transition from research lab to production line.

- Intrinsic scaling losses: Scaling from small cells to large modules with multiple interconnected cells incurs physical scaling losses.
  - Increase in cell size (approximately 1 cm<sup>2</sup> to 100 cm<sup>2</sup>): For technologies employing electrode grids (rather than transparent conducting electrodes alone), electrons must travel farther to reach an electrode in larger cells, resulting in higher resistive losses. Shadowing from electrodes reduces available light, while higher non-uniformity over large areas increases the likelihood of reverse current leakage (shunts).
  - Increase in number of cells: Longer wires dissipate more power through resistive heating. Spacing between cells reduces the active area of the module. The output current of series-connected cells is limited by the lowest-performing cell.
- Extrinsic manufacturing losses: While researchers often target the highest possible efficiencies without regard to cost, manufacturers may sacrifice efficiency to reduce cost, improve yield, and increase throughput.
  - Process: Fabrication techniques that produce high efficiencies in the lab may be ineffective or too costly for large-scale manufacturing. Increasing production scale also increases contamination risk.<sup>43</sup>
  - Materials: Research labs work primarily with small-area devices and can afford to use scarce, expensive, or high-purity materials, such as gold electrodes and high-quality glass substrates. Higher-quality materials may have fewer defects, lower recombination losses, and lower undesired absorption (e.g., in encapsulation and electrode materials).

Materials discovery has historically been a critical component of PV technology development. New active materials may reach cost and performance targets that are inaccessible using existing materials. Reliance on Earth-abundant materials bodes well for large-scale deployment, and ultra-thin, room-temperature-processed absorbers may simultaneously reduce manufacturing costs and enable flexible form factors and novel applications. Recognizing that

*New active materials may reach cost and performance targets that are inaccessible using existing materials.*

current large-scale commercialization of c-Si, CdTe, and CIGS has been driven largely by historical chance discoveries and subsequent industry momentum, a full-scale computational and experimental search is currently underway for other promising materials. Three PV technologies — copper zinc tin sulfide (CZTS), perovskites, and organics — have reached efficiencies greater than 10% within the last five years alone, suggesting that the potential for disruptive innovation remains.

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#### **FINDING**

**Emerging thin-film technologies are promising for large-scale deployment and offer unique functionality for future PV applications.**

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To transition from laboratory to pilot production line, any new PV technology must demonstrate a substantial potential advantage over current alternatives in terms of one or more performance metrics, without major disadvantages. Key considerations for measuring PV module and system performance are discussed in Box 2.6. If anticipated improvements are merely marginal, any cost or performance gains may not be evident until gigawatt-scale manufacturing is realized. At current \$1/W<sub>p</sub> investment costs for c-Si, a factory capable of manufacturing 1 gigawatt of PV capacity per year requires a billion-dollar capital investment. This high barrier to entry has thus far inhibited the rapid commercialization of many emerging technologies with insufficient perceived advantages, but it also increases the value of technologies with lower capital equipment requirements, as discussed above. Recent over-investment in c-Si raises the bar further for new and unproven alternatives.

## BOX 2.6 MEASURING PV MODULE AND SYSTEM PERFORMANCE

The dc peak power rating of a PV module or system (in  $W_p$ ) reflects its efficiency under standard test conditions (STC): 1000 W/m<sup>2</sup> irradiance, 25°C operating temperature, and air mass 1.5 (AM1.5) spectrum. But the actual ac energy output depends strongly on actual insolation, shading losses (e.g., soiling and snow coverage), module efficiency losses (e.g., at elevated temperatures or low insolation), and system losses (e.g., module mismatch, wire resistance, inverter and transformer losses, tracking inaccuracy, and age-related degradation). The energy yield (in kWh/ $W_p$ ) is a module-level performance metric that quantifies the lifetime ac energy output per unit of installed capacity. To reduce levelized cost of electricity (LCOE), efforts to advance module and balance of system (BOS) technology will focus on increasing energy yield, making heat and light management, durability, and reliability more important. An inherent tension exists between improving these technical factors and reducing the area cost (\$/m<sup>2</sup>) of the module. Energy yield is proportional to the capacity factor, as defined below.

The performance of a deployed PV system is typically characterized by its actual ac energy output per year, relative to the expected dc output. The expected output can be calculated in terms of either ideal or actual insolation, yielding two different metrics: The capacity factor (CF) compares system output to the performance of an ideal (lossless) system with identical nameplate capacity under constant peak (1000 W/m<sup>2</sup>) irradiance. The performance ratio (PR) or quality factor (Q) instead compares system output to that of an ideal system in the same location.

$$CF = \frac{\text{Actual ac output [kWh/y]}}{\text{dc peak power rating [kW}_p\text{]} \times 8,760 \text{ [h/y]}}$$

$$PR = \frac{\text{Actual ac output [kWh/y]}}{\text{dc peak power rating [kW}_p\text{]} \times 8,760 \text{ [h/y]} \times \text{Average plane-of-array irradiance [W/m}^2\text{]}/1,000 \text{ [W/m}^2\text{]}}$$

Capacity factors are commonly used to compare power generation systems. The annual capacity factor for a typical utility-scale solar PV system is around 20%, compared to 22% for solar thermal, 31% for wind, 40% for hydropower, 44% for natural gas combined cycle, 64% for coal, and 90% for nuclear plants.<sup>44</sup> Solar power systems without storage can operate only when sunlight is available; this constraint alone limits the capacity factor to the fraction of daylight hours. By accounting for geographical and temporal variations in insolation (discussed in Appendix A), the performance ratio isolates system losses and allows for a comparison of PV systems in different locations.

*The solar cell of the future may be a refined version of current commercial cells or an entirely new technology.*

## **2.6 CONCLUSION**

Predicting the future development of any technology is inherently fraught with uncertainty. While silicon technology dominates the PV market today, alternative technologies are evolving rapidly. The solar cell of the future may be a refined version of current commercial cells or an entirely new technology. Furthermore, global installed PV capacity today is a minuscule fraction of expected future deployment. Few — if any — industries have grown as fast or as unpredictably as the PV industry in recent years.

Faced with uncertain technological change and uncertain economic pressures, we abstain from betting on any particular PV technology. Instead, we view all technologies through the objective lens of application-driven performance metrics. These metrics point to three technical trends — increased efficiency, reduced materials usage, and reduced manufacturing complexity and cost — that technology leaders should target in their R&D efforts. Focusing on the unique strengths and potential applications of solar PV will help to identify windows of opportunity for future PV technology development and deployment.

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