OVERVIEW OF PHOTOVOLTAIC TECHNOLOGIES

Introduction

Solar photovoltaic modules, called "photovoltaics" or "PV", are solid-state semiconductor devices with no moving parts that convert sunlight into direct-current electricity. Although based on science that began with Alexandre Edmond Becquerel's discovery of light-induced voltage in electrolytic cells over 150 years ago, significant development really began following Bell Labs' invention of the silicon solar cell in 1954. PV's first major application was to power man-made earth satellites in the late 1950s, an application where simplicity and reliability were paramount and cost was nearly ignored. Enormous progress in PV performance and cost reduction, driven at first by the U.S. space program's needs, has been made over the last 40-plus years. Since the early 1970s, private/public sector collaborative efforts in the U.S., Europe, and Japan have been the primary technology drivers. Today, annual global module production is over 100 MW, which roughly translates into a $1billion/year business. In addition to PV's ongoing use in space, its present-day cost and performance also make it suitable for many grid-isolated applications in both developed and developing parts of the world, and the technology stands on the threshold of major energy-significant applications worldwide.

PV enjoys so many advantages that, as its comparatively high initial cost is brought down another order of magnitude, it is very easy to imagine its becoming nearly ubiquitous late in the 21st century. PV would then likely be employed on many scales in vastly differing environments, from microscopic cells integrated into and powering diamond-based optoelectronic devices in kilometers-deep wells to 100-MW or larger 'central station' generating plants covering square kilometers on the earth's surface and in space. The technical and economic driving forces favoring PV's use in these widely diverse applications will be equally diverse. However, common among them will be PV's durability, high efficiency, low cost, and lack of moving parts, which combine to give an economic power source with minimum maintenance and unmatched reliability. In short, PV's simplicity, versatility, reliability, low environmental impact, and—ultimately—low cost, should help it to become an important source of economical premium-quality power within the next 50 years.

It is easy to foresee PV's 21st-century preeminence, but the task of this chapter is a difficult one of accurately predicting PV's development trajectory toward that time. The three applications described here (Residential PV; Utility-Scale, Flat-Plate Thin Film PV; and Concentrating PV) illustrate highly feasible elements of that trajectory. These applications likely will blossom at different rates and may not all develop as forecasted. Furthermore, they are not the only major applications likely to emerge. Nevertheless, the three scenarios presented serve to give a sense of the time scale in which PV is likely to evolve from its present-day state, to the pervasive low-priced appliance of the latter half of the next century. During the time period covered by these characterizations, PV will evolve from a technology serving niche markets, to one entering and then playing an important and growing role in the world's energy markets. Up to 10% of U.S. capacity could be PV by 2030, and significant PV will be used worldwide as global demand for electricity grows.

Economic Evolution

Empirical progress in manufacturing processes is frequently displayed by means of a "learning" or "experience" curve. Conventionally, such curves are plotted using logarithmic axes, to show per-unit cost versus cumulative production volume. Most often, such a plot will produce a straight line over a very large range of actual production volumes and unit costs. The slope of that line, expressed as the percent of cost remaining after each doubling in volume, is called the "progress ratio." (Since a progress ratio of 100% would represent no learning —i.e., zero cost reduction—it would perhaps be better called a "lack-of-progress ratio.") Most manufactured goods are found to yield progress ratios between 70% and 90%, but there appears to be no generally applicable rule for assigning *a priori* expectations of progress ratios for a given process.

OVERVIEW OF PHOTOVOLTAIC TECHNOLOGIES

Figure 1 shows the experience curve over the past 20-some years for PV module prices versus total sales. Price and total sales are used as proxies for cost and manufactured volume because the actual cost and production information for the entire industry is not available. Note that, although the plotted data comprise a number of technologies, the dominant technology—crystalline silicon—has set the pace for the price-volume relation. Therefore, this figure most closely represents an experience curve for crystalline silicon PV, and this curve was used within the Technology Characterization for Residential PV systems. The 82% value falls within the range typical for manufactured goods, and the projections of crystalline-silicon module sales and prices provided within that TC are further supported by a "bottom up" analysis of the industry.

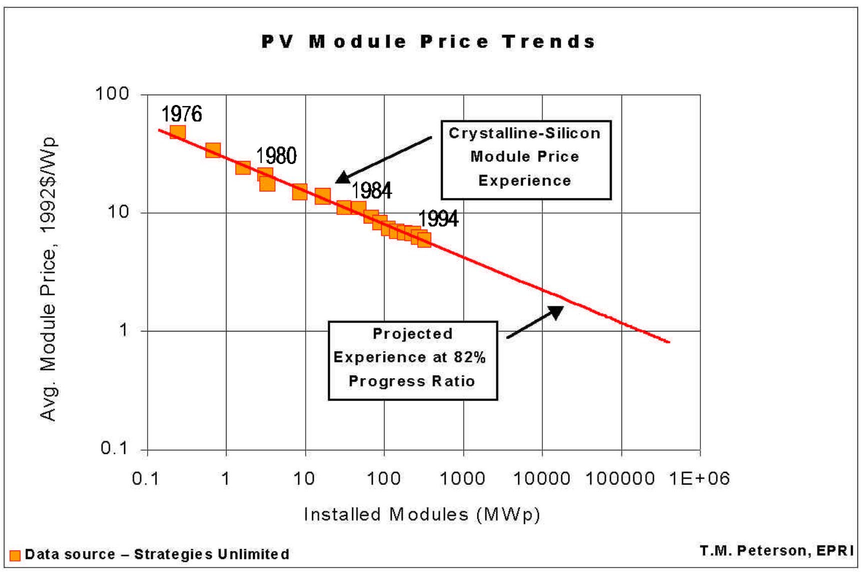

Figure 1. Learning curve for crystalline-silicon PV.

A major departure from the historical trend could be caused by emergence of a fundamentally new technology where the learning process would need to begin anew. Both thin-film and concentrator PV are likely candidates for just such a fundamental technology shift. Because historical data are not available, a great deal of uncertainty exists regarding the future costs of thin-film and concentrator PV systems which are so dependent on R&D funding and for which much industry data is proprietary.

Technology Comparison

Solar Resource: One significant difference between concentrating and other PV systems pertains to the solar resource used. Concentrating PV systems use sunlight which is incident perpendicular to the active materials (direct normal insolation). Other PV systems utilize both direct and indirect (diffuse) solar radiation. Provided in Figure 2, below, are two maps; the first is a map of direct normal insolation, the second is a map depicting global insolation for the U.S.

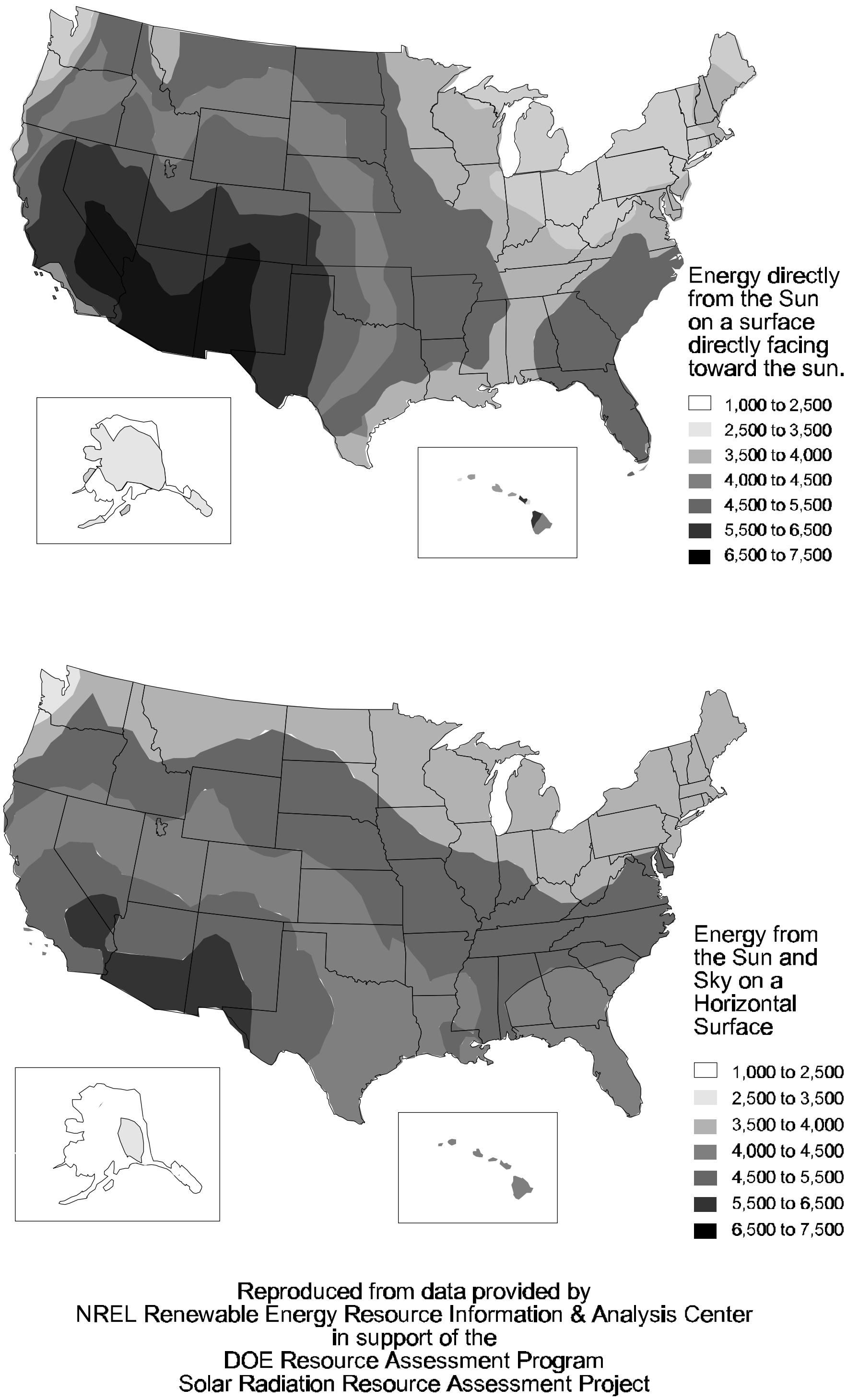

Figure 2. Direct normal insolation resource for concentrator PV (above) and global insolation resource for crystalline-silicon and thin film PV systems (below).

The main consequence of this difference is that concentrator systems should be deployed in regions that are predominantly cloud free. While other PV systems do not have this requirement, total solar resource quality does of course influence system performance. The PV Technology Characterizations take resource quality into consideration by providing performance estimates based on average and high solar resource assumptions.

Deployment: The deployment needs of the two utility scale applications described in this report are similar. Medium and large-scale deployments have significant land requirements. However, it is important to note that concentrator systems are less appropriate for very small-scale deployments (less than a few tens of kilowatts) due to their costs and complexity. Customer (building) sited PV have no land requirements, however several structural requirements are important (i.e. roof integrity and orientation, shading, pitch, etc.).

Application: The PV systems characterized here all provide distributed benefits. Residential PV systems either feed power into the grid and/or reduce customer demand for grid power. Medium and larger scale systems add capacity incrementally, and to the extent that they match load patterns, may reduce the need for major capital investments in central generation.

Modularity: PV generating systems are easily scaled to meet demand. PV systems can be constructed using one or more modules, producing from a few tens of watts to megawatts. For example, the residential PV systems characterized in this report are a few kW in size, while the concentrating and utility scale thin film PV systems are multi-megawatt applications.

Low-cost operation and maintenance: PV systems have few moving parts. Flat-plate types without tracking have no moving parts, and even two-axis tracking requires only a relatively small number of low-speed moving parts. This tends to keep operation and maintenance costs down. Indeed, some early kilowatt-scale first-of-a-kind plants demonstrated O&M costs around $0.005/kWh.

Summary

The PV applications described here are both competitive and mutually supportive at the same time. They are competitive because successful pursuit of one application will divert enthusiasm and resources from the others to some degree; but supportive, because technology and marketing advances fueled by any one of them will also somewhat aid the rest. They do compete to some extent for common markets, but they each serve sufficiently distinct needs to expect their respective niches to persist indefinitely, despite the likelihood that a single one of them may dominate the overall market.