by Kyocera, another Japanese company. The second place is held by the UK-based oil multinational BP Solar with c-Si and multi-Si plants in United States, Spain, Australia, and India. BP Solar also had two thin-film technologies in commercialization in the United States, namely a-Si and CdTe, (see footnote in Section 1.4). The biggest PV manufacturer in the USA today is Shell Solar (formerly Siemens Solar) but is held by European capital. As of this writing, of all the companies in Figure 1.11, only Astropower (US), Isofoton (Spanish), and Photowatt (French but held by Canadian investors) focus their business exclusively on photovoltaics. The others are either divisions or subsidiaries of large companies with diverse manufacturing interests.

Figure 1.3 showed the worldwide trend for various applications. Growth has been driven by distributed, grid-connected PV applications since 1996, mostly in Europe and Japan, as discussed above. There is steady growth in use of photovoltaics for diesel hybrid and communication. These are off-grid applications, typically in remote locations. Previously, operating a diesel generator 24 h a day or replacing large battery packs was the only alternative. PV diesel hybrids can be cost-effective in these cases [56].

Note that Figure 1.3 shows that large-scale, centralized solar power plants are almost nonexistent. These huge "solar electric farms" were envisioned in the early days of photovoltaics to be built in sunny arid deserts, where land was essentially worthless for other uses (note, that photovoltaics operates without water in contrast to conventional thermal power plants). These huge facilities would replace conventional power plants, at least for daytime power. The world's largest centralized PV power plant to date was installed in central California between 1984 and 1985. The operation and performance over several years was reported [57], including operation and maintenance costs [58]. After several years of operation, the installation was disassembled and the modules were sold individually on the market. Presently, the largest centralized PV power plant is 3 MW in Serre, Italy [59]. There have been several other large-scale PV installations, and their installation techniques, labor, and operation costs have been well documented. In particular, the 0.4 MW a-Si plant in California, USA [60] and the 0.48 MW concentration plant [61] in Tenerife, Spain are notable because they do not use the ubiquitous unconcentrated c-Si technology.

1.8 CRYSTALLINE SILICON PROGRESS AND CHALLENGES

Figure 1.9 showed that c-Si, as either single or multicrystalline wafers or ribbons, was responsible for almost 90% of worldwide PV production in 2001. How did its dominance occur?

First, there was a tremendous worldwide scientific and technical infrastructure for Si starting in the 1960s. Huge government and industrial investments were made in programs for understanding the chemical and electronic properties of Si, how to grow it with the required purity and crystalline structure, and to create the equipment needed to perform all the processing steps. The motivation was not just idle scientific curiosity, but rather the competitive drive to manufacture increasingly complex integrated circuit chips, which created first the analog then the digital electronic revolutions leading to our current information, entertainment, and telecommunications industries. The promise of wealth and market dominance led public and private organizations to unlock many