

RESIDENTIAL PHOTOVOLTAICS

1.0 System Description

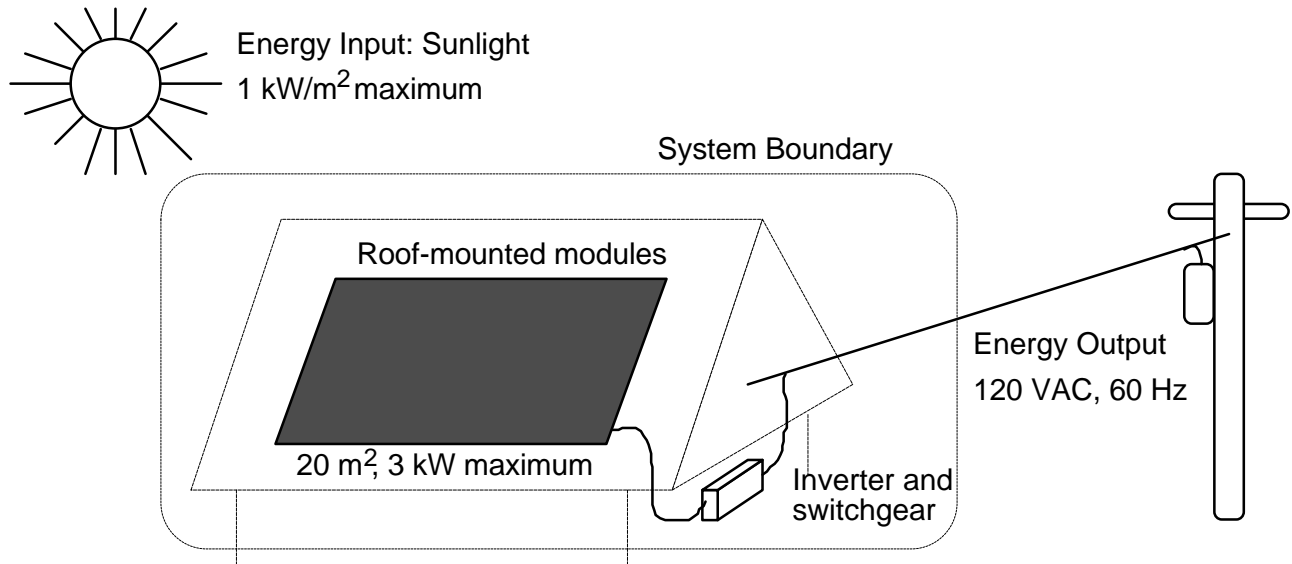


Figure 1. Residential photovoltaic energy system schematic.

Photovoltaic (PV) modules are large-area solid-state semiconductor devices that convert solar energy directly into electrical energy. Individual PV modules produce direct-current (dc) electricity, and are available in sizes from 10 W to 300 W. The actual power output depends upon the intensity (W/m^2) of sunlight, the operating temperature of the module, and other factors. PV modules are designed and sized to produce the desired electrical output. Addition of electrical power conditioning components (electrical switches, diode protection circuits, dc-to-ac inverters, etc.) are required to interface the PV output with the electrical load. The resulting assembly of components is known as the photovoltaic system.

A residential PV system was selected for this Technology Characterization because it is a well-defined application of the technology, it can have a significant impact on energy use within the United States, and it is an application that effectively utilizes the attributes of PV systems for maximum economical benefit. Customer-sited, grid-tied PV systems are expected to be an early large-scale market for PV energy systems, because these systems take maximum economical advantage of PV technology's positive attributes. Customer siting means that the PV systems is located at, or very near, the point of use, and includes applications like residential roof-top PV systems, commercial-building roof PV systems, and building-integrated PV systems. This report examines residential PV systems, but many of the comments pertain to other types of customer-sited PV systems as well.

The residential rooftop PV system (Figure 1) considered in this report has no energy storage. Some (or most) of the energy may be used on site, and a power purchase agreement allows the remaining electricity produced to be fed into the existing utility grid. These PV systems are generally between 1 and 5 kW, and the nominal system considered in this report is 3 kW. (In reality, for this characterization, the system size is held constant at 20 m^2 and the dc rating increases over time to 4 kW). The PV modules are mounted on the roof or, in the future, may be specifically designed as roofing elements (e.g., PV shingles, etc.). The modules characterized here use crystalline-silicon solar cells. In the future, by about 2020, advanced PV technologies – crystalline-silicon ribbon or sheet, and various thin-film (amorphous

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silicon, cadmium telluride, or copper indium diselenide) materials may be used. While no energy storage is included in the system presented here, energy storage may become economical in the future. The PV modules described here are wired to a single dc-to-ac inverter or, in the future, may include their own individual dc-to-ac inverter. The ac power is tied to the grid through protective switches which disconnect the PV system should the utility power be disrupted. The system costs described here do not include the roof or the building, which are assumed to already exist.

Two sets of systems are described here - that for a single homeowner, who finances and owns the system - and the neighborhood bulk system by a utility or other generating company which installs PV systems on the roofs of many clustered customers. For the latter, the utility finances and owns the systems and achieves certain economies of scale in capital cost, installation, and operations and maintenance (O&M).

2.0 System Application, Benefits, and Impacts

Photovoltaic energy systems are currently used wherever relatively small electrical loads (typically less than 100 kWh/month) cannot be conveniently powered by an existing utility grid. As prices for PV technology decline through technology improvements and increased manufacturing automation, PV energy systems will become a viable option for an increasing diversity of loads requiring more power than the typical off-grid small systems used today. The unique advantages of photovoltaics – modularity, good match to many diurnal load patterns, low O&M, environmentally benign, renewable energy source – are expected to be important factors in early cost-effective applications of PV energy systems.

In order for PV to make a significant contribution in the U.S., PV generation will have to interconnect with the electrical grid and compete with existing electrical-energy generation sources. The cost of meeting utility demand is not constant but varies according to the level of load. Times of peak load are associated with the highest cost electricity. This high cost is due to using generation sources with high fixed costs and low efficiency (but often with low or depreciated capital costs), losses due to increased loading of the transmission and distribution (T&D) system during peak periods, and increased size of the T&D system to handle peak loads. The net result is that the full cost for delivering electricity to a customer during summer peaks can be as high as \$0.40/kWh [1,2]. Although PV only generates electricity when the resource is available, this generation tends to correlate reasonably well with daily demand patterns, thereby delivering its output during times of highest value. In order to reduce peak loads, some utilities have employed time-of-day pricing, a strategy which provides incentives to users to implement energy conservation measures and adopt on-site generation sources that reduce peak loads to the central utility. PV energy is well suited to compete with other peak power sources because the PV energy profile roughly matches the electrical load profile in many regions of the country.

Besides meeting peak power requirements, PV is modular, i.e., size and location can be optimized to meet residential and utility requirements. Some of the potential advantages of PV include:

1. PV can capture benefits of distributed electrical energy generation where utility costs associated with transmission and distribution are reduced by locating the electrical generation source close to the point of use [1,2,3,4].
2. Customer-sited PV systems help minimize balance-of-system costs because there are minimal costs associated with site acquisition and preparation and there is generally a pre-existing utility connection to the site [5,6,7].
3. Customer-sited PV fits into the more flexible deregulated utility environment where the generation is no longer necessarily owned by the utility. For example, the residential PV system could be owned by the utility, by an independent power producer who “rents” the rooftop from the residential owner, or by the resident.

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In addition, PV uses a renewable energy source (sunlight) and produces no emissions during operation. Surveys indicate that many customers are willing to pay a premium for a “green” product (in this case, electricity) that has environmental benefits when compared to competitive products [8].

Because of the benefits described above, residential PV systems are expected to be one of the first grid-tied applications of PV to reach cost effectiveness with existing electrical-energy sources. Residential PV systems also represent a potentially large market. There are approximately ten million single-family homes located in regions of the United States that have above-average sunshine and suitably tilted roofs with unshaded access to direct sunlight. This market has a potential of over 30 GW [9]. For single homeowners to fully realize the potential of residential roof PV energy systems, it would be necessary for the power purchase agreement between the utility and the system owner to reflect some of the economical values described above. Utilities that own neighborhood bulk systems include New England Electric Systems (NEES) in Gardner, MA [10] and the Sacramento Municipal Utility District (SMUD) [11].

PV solar energy provides a number of other benefits besides the value of the energy. Some of these benefits include the following: no fuel or water consumption; low maintenance; improved national energy security; economically important U.S. export technology; and avoidance of CO₂ generation. See a companion report on Utility-Scale, Flat-Plate, Thin-Film Photovoltaic Systems for a more complete discussion on some of these ancillary benefits [12]. Because of the advantages cited above and concerns associated with global climate change, the U.S. Department of Energy announced an initiative to promote the installation of one-million roof top systems (solar thermal and PV), by the year 2010 [13]. The Million Solar Roofs Initiative is a recognition of the readiness of residential and commercial roof solar energy systems to become a significant energy source for the U.S. The technology and regulatory improvements developed under this initiative will help facilitate the more rapid introduction of residential photovoltaic energy systems in the U.S., as costs are driven down. Cost and other technology assumptions and issues are discussed below.

3.0 Technology Assumptions and Issues

Residential PV systems are not yet cost competitive with grid-connected electricity; and most of the systems installed to date were subsidized. Many were installed in Japan and in Europe, where there is significant public support of clean energy sources. The bulk of PV modules sold today, and of residential PV systems installed to date, use one-sun modules with crystalline-silicon solar cells. Also, most PV systems are used today in applications where there is no low-cost source of grid electricity.

The technology progress described in this report assumes an orderly expansion and development of the market for residential PV systems, and continued improvement in both cost and performance of the PV modules and balance-of-system components. As the market for these systems increases, installation costs and standardization, along with improved manufacturing processes and increased conversion efficiency, are expected to reduce various cost components significantly. Achievement of the market expansion and technology improvements, however, are not certain and will require significant further public and private investment. Identification of early cost-effective markets and marketing of “green” power will be critical for market expansion in the early years when PV system costs are still much higher than grid-tied electricity. This stage can be assisted through publicly and privately financed programs, including the Million Roofs Solar Initiative, to help identify and develop the interim high-value markets described in Section 2.

Further technology improvements to reduce the cost and improve the performance of PV modules and balance-of-system (BOS) components are required. Substantial reductions in costs and improvements in efficiency have been achieved over the past 20 years. This progress has been greatly assisted by publicly funded R&D. Continuation of this R&D will be instrumental for further progress since the profit margins in the PV industry have been insufficient

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to support an adequate private R&D program. The recent progress in crystalline-silicon PV technology has been greatly assisted by publicly funded R&D programs like the DOE PV Manufacturing Technology (PVMaT) program and publicly-funded, DOE laboratory and university R&D. Some of the technology improvements and product design changes that have helped reduce cost include the following: casting of larger ingots to improve the productivity of crystal-growth; replacement of inner-diameter saws with wire saws to improve the productivity of slicing ingots; improvement of the yield and throughput of cell fabrication processes, e.g., diffusion and antireflection coating; use of larger area cells to reduce the cost of operations that scale per piece, e.g., screen print and cell tab; and use of larger area modules to reduce the costs of components that scale per module, e.g., interconnection box and module testing. Compared to the present crystalline-silicon PV modules, thin-film PV technology promises further cost reductions because of its inherently lower material and energy content, and to a product design that could be more manufacturable, planar processing of large-area substrates. DOE and private (e.g., EPRI) R&D programs were instrumental in the development of this completely new technology, and the first large-scale, >5 MW/year, thin-film PV plants started operations in 1997. Finally, BOS components are a significant cost factor in PV systems. PV modules with integrated inverters or with building-integrated features may have a significant impact on grid-tied PV system costs.

4.0 Performance and Cost

Two sets of performance and cost indicators for the residential PV system being characterized in this report are presented. Table 1 shows figures for a single homeowner, who finances, owns and operates a roof-top system.

Table 2 shows figures for a compact neighborhood grouping of residential systems, where a utility or private developer owns, finances, and provides maintenance. Table 2 illustrates the influence that economies of scale have on system costs. Cost Of Energy figures should be prepared from Table 2, because while the homeowners realize an energy savings, they do not sell power to themselves or take depreciation or tax credits unless they are self-employed.

4.1 Evolution Overview

The PV module efficiency and cost projections reflect the expected evolutionary development of crystalline-silicon PV modules. The physics of high-efficiency crystalline-silicon laboratory solar cells is now very well understood, and the best laboratory cell performance today, 24%, is nearing best theoretical expectations, around 30% [14,15]. Hence, the best laboratory cell performance is expected to increase between 25% and 28% by 2030. The efficiency of commercial crystalline-silicon PV modules under standard rating conditions is, therefore, assumed to grow slowly to 20%, which corresponds to about 80% of the performance for the expected best laboratory cell performance of 25%.

Table 1. Performance and cost indicators (C-Si residential PV systems -- individual/single-home basis*).

INDICATOR NAME	UNITS	Base Case 1997		2000		2005		2010		2020		2030	
			+/- %		+/- %		+/- %		+/- %		+/- %		+/- %
Unit Size	kW _{ac}	2.3		2.6		2.8		3.0		3.2		3.4	
Unit Size	kWp _{dc}	2.8		3.2		3.4		3.6		3.8		4.0	
Unit Size (module area)	m ²	20		20		20		20		20		20	
PV Module Performance Parameters													
PV Module (dc) efficiency	%	14		16	10	17	15	18	20	19	20	20	25
Inverter Efficiency	%	90		91	10	92	15	93	20	94	20	95	25
ac System Efficiency	%	11.3		13.1	10	14.1	15	15.1	20	16.1	20	17.1	25
Annual System Performance in Average-Insolation Location (global sunlight, in plane, 1800 kWh/m ² -yr)													
ac Capacity Factor	%	20.5		20.5		20.5		20.5		20.5		20.5	
Energy/Area	kWh/m ² -yr	204		236		253		271		289		308	
Energy Produced	kWh/yr	4,082		4,717		5,067		5,424		5,787		6,156	
Annual System Performance in High-Insolation Location (global sunlight, in plane, 2300 kWh/m ² -yr)													
ac Capacity Factor	%	26.3		26.3		26.3		26.3		26.3		26.3	
Energy/Area	kWh/m ² -yr	261		301		324		347		370		393	
Energy Produced	kWh/yr	5,216		6,028		6,475		6,930		7,394		7,866	
Capital Cost (1997\$)													
dc Unit Costs													
PV Module Cost	\$/Wp	3.75		3.04	30	2.34	30	1.80	30	1.07	30	0.63	30
Power-Related BOS	\$/Wp	1.50		1.22	30	0.94	30	0.72	30	0.43	30	0.25	30
Area-Related BOS	\$/m ²	170		138	30	106	30	82	30	48	30	29	30
Area-Related BOS	\$/Wp	1.21		0.86	30	0.62	30	0.45	30	0.25	30	0.14	30
Total BOS	\$/Wp	2.71		2.08	30	1.56	30	1.17	30	0.68	30	0.40	30
System Total	\$/Wp	6.46		5.12	30	3.90	30	2.98	30	1.75	30	1.03	30
System Total	\$	18,100		16,400	30	13,300	30	10,700	30	6,600	30	4,100	30
ac Unit Costs	\$/Wp	7.86		6.30	30	4.74	30	3.58	30	2.08	30	1.21	30
System Operations and Maintenance Cost													
Maintenance (annual)	\$/m ² -yr	2.0		2.0	30	2.0	50	2.0	50	2.0	50	2.0	50
Total Annual Costs	\$/yr	40		40	30	40	50	40	50	40	50	40	50

Notes:

1. Area-related BOS costs restated to their "power-related" equivalent.
2. The columns for "+/-%" refer to the uncertainty associated with a given estimate.
3. Residential system installation (i.e. "construction") requires several hours or days.

^b This table reflects an "individual system" scenario, while Table 2 displays further cost reductions possible through volume purchasing.

Table 2. Performance and cost indicators (C-Si residential PV systems -- network neighborhood)

INDICATOR NAME	UNITS	Base Case		2000		2005		2010		2020		2030	
		1997	+/- %		+/- %		+/- %		+/- %		+/- %		+/- %
Unit Size	kW ac	2.3		2.6		2.8		3.0		3.2		3.4	
Unit Size	kWp dc	2.8		3.2		3.4		3.6		3.8		4.0	
Unit Size (module area)	m ²	20		20		20		20		20		20	
Number of Houses	--	130		385		357		333		313		294	
Plant Size	kW ac	299		1,001		1,000		999		1,002		1,000	
PV Module Performance Parameters													
PV Module (dc)	%	14		16	10	17	15	18	20	19	20	20	25
Inverter Efficiency	%	90		91	10	92	15	93	20	94	20	95	25
ac System Efficiency	%	11.3		13.1	10	14.1	15	15.1	20	16.1	20	17.1	25
Annual System Performance in Average-Insolation Location (global sunlight, in plane, 1800 kWh/m2-yr)													
ac Capacity Factor	%	20.5		20.5		20.5		20.5		20.5		20.5	
Energy/Area	kWh/m2-yr	204		236		253		271		289		308	
Energy Produced/Unit	kWh/yr	4,082		4,717		5,067		5,424		5,787		6,156	
Annual System Performance in High-Insolation Location (global sunlight, in plane, 2300 kWh/m2-yr)													
ac Capacity Factor	%	26.3		26.3		26.3		26.3		26.3		26.3	
Energy/Area	kWh/m2-yr	261		301		324		347		370		393	
Energy Produced/Unit	kWh/yr	5,216		6,028		6,475		6,930		7,394		7,866	
Capital Cost (1997\$)													
dc Unit Costs													
PV Module Cost	\$/Wp	3.15		2.55	30	1.97	30	1.51	30	0.90	30	0.53	30
Power-Related BOS	\$/Wp	1.30		1.05	30	0.81	30	0.62	30	0.37	30	0.22	30
Area-Related BOS	\$/m2	150		122	30	94	30	72	30	43	30	25	30
Area-Related BOS	\$/Wp	1.07		0.76	30	0.55	30	0.40	30	0.22	30	0.13	30
Total BOS	\$/Wp	2.37		1.81	30	1.36	30	1.03	30	0.59	30	0.35	30
System Total	\$/Wp	5.52		4.37	30	3.33	30	2.54	30	1.49	30	0.88	30
System Total	\$	15,500		14,000	30	11,300	30	9,100	30	5,700	30	3,500	30
ac Unit Costs	\$/Wp	6.72		5.34	30	4.04	30	3.05	30	1.77	30	1.04	30
System Operations and Maintenance Cost													
Maintenance (annual)	\$/m ² -yr	2.0		2.0	30	2.0	50	2.0	50	2.0	50	2.0	50
Unit Annual Costs	\$/yr	40		40	30	40	50	40	50	40	50	40	50

Notes:

1. The columns for "+/-%" refer to the uncertainty associated with a given estimate.
2. Complete system installation (i.e. "construction") on all houses is assumed to require six months.

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Future years, beginning about 2020, may also see the introduction of building-integrated PV elements (e.g., PV shingles, etc.) that have much improved aesthetics and may further reduce net system costs by replacing other roofing materials [7, 11]. Future years might also see the introduction of thin-film PV technologies [12]. The building-integrated PV and thin-film PV technologies have lower performance compared to crystalline-silicon PV modules at present. The module efficiency is a very important issue for commercial and residential roof PV systems because the available space is fixed. Despite possible improvements in areal (\$/m²) or power (\$/W) costs of these advanced PV technologies, their introduction into residential and commercial roof PV systems will probably require performance levels comparable to crystalline-silicon PV. The expected evolutionary development of thin-film PV modules is reviewed in a companion report [12]. The more favorable cost reductions projected for thin-film PV technology would reduce projected system costs in Tables 1 and 2 using crystalline-silicon PV technology projections proportionately.

4.2 Performance and Cost Discussion

As indicated in Tables 1 and 2, the physical size of an individual residential PV system is assumed to remain fixed at 20 m², fitting within the unobstructed space available on the south-facing slope of a typical residential rooftop. DC unit ratings increase from 2.8 kW in 1997 to 3.2 kW in 2000 to 4.0 kW in 2030. The rated dc module efficiency and rated dc power are for standard reporting conditions (1 kW/m², 25°C/77°F). The rated ac power is the product of the dc module rating and the inverter efficiency. The system operating efficiency is the product of the module efficiency, the inverter efficiency, and an additional factor of 0.9 to account for operation away from standard rating conditions [16].

The PV output at any given time is directly proportional to the available solar energy (insolation). The cost of producing PV solar energy is therefore inversely proportional to the solar insolation. The solar insolation depends upon latitude, local climate, and PV module mounting. PV module mounting refers to positioning of the PV module with respect to the position of the sun – a tracking PV array collects the maximum available sunlight by pointing the array at the sun as the sun changes position in the sky, while, with a fixed array, the solar intensity changes continuously during the day. Residential systems generally use fixed arrays. Insolation varies between 1.6 and 2.4 MWh/m²-yr for a south-facing, fixed array. This report considers both average-insolation (1.8 MWh/m²-yr) and high-insolation (2.3 MWh/m²-yr) locations. The high insolation location is of particular interest for early cost-effective applications. The annual energy production is the product of the system efficiency and the solar insolation. The ac capacity factor is defined as the annual energy production divided by the product of the rated ac power and the number of hours in a year (8,760).

For Table 1, the PV module, power-related BOS, and area-related BOS costs for the base year were based on the first few large utility-sponsored residential PV system projects (SMUD's PV Pioneers), where houses were widely dispersed. These costs were compared to costs independently estimated using standard construction-industry project estimation procedures [17]. The independent estimate considered both low-voltage and high-voltage dc systems, and considered ac PV modules (PV modules with integrated inverters). At present, low-voltage inverters cost less per rated capacity than high voltage inverters since similar inverters are already manufactured commercially at low volumes for other applications (uninterruptible power supplies). However, low-voltage systems have higher area-related BOS costs due to increased wiring requirements. The ac PV modules have the lowest area-related BOS cost since there is no longer a separate dc system, but the inverters for ac PV modules presently have a higher cost. A large manufacturing volume and some technology improvements (e.g., integrated circuits for power supplies) will be required to reduce the cost of inverters for ac PV modules. Despite these differences, the net result is that the three types of systems had similar total BOS costs. The independent estimate yielded costs similar to the large utility-sponsored project. Most of the systems installed to date use a low-voltage system, which was considered in this report. It should also be noted that the power-

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related BOS costs include the utility costs for the interconnection, such as replacing a home's meter and adding the disconnect switches to allow for net metering.

For Table 2, a compact neighborhood of houses with rooftop PV systems is assumed. Beginning in 1985, NEES installed 60 kW of PV on existing residential rooftops in Gardner, MA, plus 40 kW in commercial applications in three nearby states [10]. NEES did not sell the PV systems when it divested its generating assets [18]. A larger series of projects was undertaken by SMUD with their "Residential PV Pioneer" projects, which ranged from 87 kW on 25 homes to 400 kW on 119 homes [11]. In Table 2, for 1997, plant size is assumed to be 0.299 MW based on placing 2.3 kW_{ac} systems on 130 homes. For 2000 and later, plant size is estimated at 1.0 MW, assuming systems installed on 385 houses in 2000 to 294 houses in 2030. Experience will lead to an optimal number of homes in the grouping. The compact neighborhood and bulk purchases translate into lower PV module, BOS, and O&M costs relative to similar values in Table 1.

Estimation of costs for highly evolving products like photovoltaic modules and systems over several decades is a very difficult task. One method is to extrapolate from historical data. A useful tool for performing extrapolations of the costs of manufactured products from historical data is the learning curve [19-21]. This method is derived from examination of cost data for many different industries, which has found that the cost of the product in constant dollars is a geometric function of the product's cumulative volume. The price reduction expected for a doubling of volume is known as the learning curve factor. The learning curve may be combined with an annual projected growth rate to estimate the annual reduction in product cost.

Data for the price of PV modules, as a function of cumulative volume, has been analyzed by several groups, and they reported learning curve factors between 0.68 and 0.82 [19-21]. The more conservative learning curve factor of 0.82 was used in this study because analyses of many other industries have found similar values [21]. This value means that a doubling of the cumulative volume of PV modules sales will reduce the cost of PV modules to 82% of its previous value. The annual growth rate in PV module sales has been between 15-20% in recent years [22,23]. Given the strong demand for PV modules and the broad interest in accelerating adoption of PV energy (e.g., Million Solar Roofs Initiative), an annual growth rate of 20% can be conservatively assumed. A learning curve factor of 82% and assumed growth rate of 20% yield an estimated price reduction of 5% per year. An annual growth rate of 20% and annual cost reduction of 5% is used to generate the projections for the years 2000-2030 (Table 3). The price of \$3.15 in 1997 is based on the estimated module price of one of the lowest recent bid system prices (\$5.76/W_p for SMUD PV Pioneer residential PV systems). The average wholesale price of crystalline-silicon PV modules has stayed around \$4.00/W_p in recent years because of increased demand and constrained capacity. Table 3 illustrates the potential of the technology, given a more mature market.

Table 3. Projections of crystalline-silicon photovoltaic module sales and prices.

Year	Module Effic. (%)	Annual Sales (MW)	Price (\$/W _p)	Sales (\$M)	Module (\$/m ²)
1997	14	84	3.15	265	441
2000	16	174	2.55	444	408
2005	17	433	1.97	853	335
2010	18	1,078	1.51	1,628	272
2020	19	6,678	0.90	6,010	171
2030	20	41,347	0.53	21,914	105

The prices in Tables 1, 2, and 3 are all in constant 1997 dollars, excluding inflation. Therefore, if the average inflation rate also happened to equal our average annual cost reduction of 5%, the price of PV modules in 2030 would be \$3.15

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in current-year dollars. Also note that *Price* does *not* refer to the manufacturing cost and as such reflects overhead factors as marketing, distribution, and research and development.

The validity of using the learning curve to extrapolate PV module costs to the low values after year 2010 should be assessed because the nature of the industry might change at the larger sales volumes or other more fundamental (i.e., physical) limits might arise. A second type of cost extrapolation was used to check the validity of the preceding table. This cost estimate used a “bottom up” analysis of the industry; i.e., the manufacturing cost is estimated at different production volumes for a specific proposed factory and manufacturing process. A detailed study was recently completed by a European research group [24]. The study estimated the manufacturing cost of crystalline-silicon and of thin-film PV modules at a production level of 500 MW per year. The European study estimated a *manufacturing cost* of \$1.30/W for both the crystalline-silicon and thin-film PV at a production level of 500 MW per year. The manufacturing cost of \$1.30/W compares well with our learning curve-based, extrapolated *price* of \$1.92/W at a production level of 433 MW per year. This comparison gives confidence in using the learning curve to extrapolate PV module costs.

There is less data available for BOS components to estimate learning curve factors. Substantial cost reductions are still possible in the small inverters used for residential systems through design changes (reduce high-cost ferromagnetic materials with silicon devices), technology improvements (e.g., integrated circuits for power supplies), and high-volume manufacturing [25]. Improvement in system design and standardization of components will reduce area-related BOS (i.e., installation and wiring) costs, and a substantial impact would be expected with the successful development of an ac PV module. Some observers suggest that there is little learning improvement available in BOS due to the maturity of the industry; for example, the costs of installation and wiring are well known from the much larger construction industry [26]. Nevertheless, a recent project achieved a 50% reduction in BOS costs for ground-mounted PV systems through improvements in integration of the system components [27]. As was the case for modules, a learning curve factor of 0.82 and a growth rate of 20% were used, and these correspond to an estimated cost reduction per annum of 5%, for both power- and area-related BOS. The uncertainties in BOS costs in later years are larger because of the difficulty in projecting the performance of a maturing industry with multiple technology options.

As pointed out earlier, PV systems have very low operation and maintenance costs. A recent study examined the performance of a residential PV energy system after ten (10) years of operation [28]. This study found that the system, with the exception of some of the power conditioner components, was highly reliable and had minimal O&M costs. The report found an average annual O&M cost of only \$52. The O&M cost represents a maintenance contract in Table 1 when the system is owned by the homeowner. In Table 2, it represents the cost of system monitoring and maintenance if the system is owned by the utility or a third party. The components and system are anticipated to have 20-year warranties, so no cost for component replacement was included.

5.0 Land, Water, and Critical Materials Requirements

No land or water resources are required for operation of the system (Table 4), which is installed on existing structures and uses rainwater for cleaning. The only critical material for crystalline-silicon PV modules is high-purity silicon. Silicon is one of the most abundant elements in the earth’s crust, so the issue is not availability but the cost of purification. High-purity silicon is typically produced as either pellets or chunks of fine-grained polycrystalline silicon and is commonly known as “polysilicon feedstock.”

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Table 4. Resource requirements.

Indicator Name	Units	Base Year					
		1997	2000	2005	2010	2020	2030
Land	ha/MW	0	0	0	0	0	0
	ha	0	0	0	0	0	0
High Purity Silicon	MT/MW	6.9	5	4	3	2	1
Water	m ³	0	0	0	0	0	0

The availability of polysilicon feedstock is currently an issue for the crystalline-silicon photovoltaic industry, so its availability to meet future large markets needs to be addressed [29,30]. The crystalline-silicon photovoltaic industry used approximately 1,000 MT of polysilicon feedstock in 1995. It obtains most of this material as off-specification material from the electronic-grade polysilicon feedstock industry. The quantity of silicon consumed by the photovoltaic industry is about 10% of the total electronic-grade polysilicon feedstock production. The price and availability of this material is affected by the business cycle of the semiconductor electronics industry. For example, there was excess capacity in the electronic-grade polysilicon feedstock industry between the years 1985 and 1993 – so that the excess feedstock from the electronic-grade silicon industry was both plentiful and inexpensive. Due to the phenomenal growth rate of the semiconductor electronics industry over the past three years, demand for electronic-grade silicon now exceeds supply – which has led to the present situation of a tight polysilicon feedstock supply for the photovoltaic industry. Again illustrating the business-cycle nature of the polysilicon feedstock supply, one industry observer notes that announced capacity additions in the electronic-grade polysilicon industry, coupled with the more stringent specifications for advanced integrated-circuit production, are likely to lead to a doubling of the quantity of excess silicon available to the photovoltaic industry within the next five years [30]. The average growth rate of electronic-grade polysilicon feedstock between 1975 and 1995 was around 10%, while the average growth rate of the photovoltaic industry is projected to be around 20%. Hence, the photovoltaic industry will become too large to use excess polysilicon feedstock from the electronic-grade polysilicon feedstock industry at some point in the future using current technology.

To meet large future markets, the crystalline-silicon photovoltaics industry will need to develop its own source of polysilicon feedstock. The European study projected that using current technology, a photovoltaic-grade polysilicon feedstock could be produced for about \$20/kg [24]. There are R&D programs that are attempting to develop technologies to reduce this cost further [31]. Present wire-saw technology can slice silicon wafers on 400- μ m centers, which corresponds to about 7 g/W for 15%-efficient cells with 90% manufacturing yield. At \$20/kg, the 7 g/W corresponds to \$0.14/W. This figure will not limit the industry through the year 2010. By the year 2010, new crystalline-silicon photovoltaic technologies that use much less silicon per watt are anticipated to become widely available. For example, ribbon and sheet crystalline-silicon technologies, which can have effective silicon thicknesses between 100 and 200 μ m, are just becoming commercially available. The thin-layer crystalline-silicon film cells that are currently under development have thicknesses between 10 and 50 μ m, and might be available after the year 2010.

Using the previous assumptions of 15%-efficient modules and 90% manufacturing yield, the polysilicon usage and cost for these technologies are summarized in Table 5.

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Table 5. Projected silicon feedstock usage and cost for various crystalline-silicon photovoltaic technologies.

Technology	Thickness μm	Usage g/W	Cost \$/W _p	Cost \$/m ²
Wire Saw	400	6.9	0.138	20.70
Ribbon	200	3.5	0.069	10.35
Sheet	100	1.7	0.035	5.25
Thin-layer	50	0.9	0.017	2.55
Thin-layer	10	0.2	0.003	0.45

Note: Calculations assume a module efficiency of 15%, a manufacturing yield of 90%, and a polysilicon feedstock cost of \$20/kg.

This analysis shows that the cost impact of the polysilicon feedstock is progressively less for the advanced technologies available in the future. Based on the anticipated establishment of a polysilicon feedstock production for photovoltaics at around \$20/kg and the technology improvements available in crystalline-silicon photovoltaics, polysilicon feedstock is not considered a fundamental issue limiting continued crystalline-silicon photovoltaic industry expansion. However, as with any developing business requiring large capital expenditures, there may be periods of difficulty until a dedicated photovoltaic-grade silicon supply is established. Of course, the emergence of thin-film technologies in future years may also obviate polysilicon feedstock limits on PV module production. Critical material issues associated with thin-film PV production are reviewed in a companion report [12].

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