# Expert Assessments of Future Photovoltaic Technologies

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Subjective probabilistic judgments about future module prices of 26 current and emerging photovoltaic (PV) technologies were obtained from 18 PV technology experts. Fourteen experts provided detailed assessments, including likely future efficiencies and prices under four policy scenarios. While there is considerable dispersion among the judgments, the results suggest a high likelihood that some PV technology will achieve a price of $\$1.20/W_p$ by 2030. Only 7 of 18 experts assess a better-than-even chance that any PV technology will achieve $\$0.30/W_p$ by 2030; 10 of 18 experts give this assessment by 2050. Given these odds, and the wide dispersion in results, we conclude that PV may have difficulty becoming economically competitive with other options for large-scale, low-carbon bulk electricity in the next 40 years. If $\$0.30/W_p$ is not reached, then PV will likely continue to expand in markets other than bulk power. In assessing different policy mechanisms, a majority of experts judged that R&D would most increase efficiency, while deployment incentives would most decrease price. This implies a possible disconnect between research and policy goals. Governments should be cautious about large subsidies for deployment of present PV technology while continuing to invest in R&D to lower cost and reduce uncertainty.

## Introduction

Sunlight is a vast source of energy: if all that reaches the earth's surface could be used, the world's energy needs could be met more than 9000 times over (*1*). Solar power is also attractive as a low-carbon source for mitigating the threat of global climate change. For these and other reasons, the idea of using solar energy is popular (*2*).

Solar photovoltaics (PV) convert sunlight into electricity. However, the intermittent nature of sunlight presents a challenge (*3*). Even if this were satisfactorily addressed, PV capital costs continue to be high. Single PV module prices are in excess of $\$4.50/W_p$, and balance of system (BOS) costs, which include installation, wiring, and power electronics, roughly double this price (*4*). $W_p$ ("watts peak") is the output under standard test conditions, roughly equivalent to the "peak" noon output at midlatitudes. Of course, prices are lower for purchase in bulk. Module prices around $\$3.50/W_p$, with a total system price under $\$6/W_p$, can be realized with volume purchases (*5, 6*). At least one manufacturer is reporting module prices under $\$2.50/W_p$ (*7*). While module prices have decreased by nearly an order of magnitude since the early 1980s, they are still high when compared with most other low-carbon power generation options, especially when scaled by availability, that is, price in $\$/W_{\text{installed capacity}}$ divided by capacity factor. Thus, we estimate capital costs today as follows:

PV: $\sim\$5/W_p/\leq 0.2$ = $\geq\$25/W$ (*3, 5, 6*)
solar thermal: $\sim\$4.2/W$ / $\sim 0.24$ = $\sim\$17/W$ (*8, 9*)
wind: $>\$1.6/W$ / 0.4 = $>\$4/W$ (*10*)
nuclear: $\geq\$4/W$ / 0.9 = $\geq\$4.4/W$ (*11, 12*)
coal with carbon capture and storage: $\sim\$4/W$ / 0.9 = $\sim\$4.4/W$ (*13, 14*)

In 2004, the Solar Energy Industry Association (SEIA) published a roadmap predicting system prices of $\$2.33/W_p$ by 2030 assuming high R&D funding and high deployment incentives (*15*). If BOS is half the total expense, then this implies module prices of $\sim\$1.15/W_p$. The Solar America Initiative (SAI) has set a target of $\$1.25/W_p$ by 2015. Others have made similar predictions about future prices for specific PV technologies over the coming decade (*16–20*). Recent work presents limited expert opinion on future PV performance, used to inform an economic analysis (*21*). This paper provides detailed assessments of the expected future performance of 26 PV technologies from 18 individual PV experts.

## Methods

Using formal methods previously developed in studies of experts' uncertainty about climate science (*22–24*), we obtained probabilistic judgments of the future performance of 26 new and emerging PV technologies (Table 1) from eighteen PV experts (Table 2). We elicited and report all price estimates in terms of $\$/W_p$. This is because to estimate the levelized cost of electricity (LCOE, in ¢/kWh), one must know several quantities with which not all experts are familiar: the BOS cost (in $\$/W_p$), capacity factor (average annual output/peak output), module and system lifetimes, operation and maintenance (O&M) costs, and capital charge. Several of these factors also depend critically on location.

We asked the experts to assess the probability that module capital prices of each technology will be $\leq\$1.20/W_p$ and $\leq\$0.30/W_p$ in 2030 and in 2050. The lower level was chosen as the approximate target for PV to be competitive in supplying bulk, low-carbon AC power. Initial respondents told us this level was "way too low." Accordingly, we added the second "more realistic" price target. Which benchmark one believes to be appropriate depends on assumptions about the characteristics of the future electricity system and the relative costs of other low-carbon technologies. For most of these individual PV technologies, one or more of a subset of 14 of the experts also considered the technical barriers to success for the specific PV technology. The experts then provided probabilistic judgments of expected ranges of future efficiencies and prices in 2030 under four policy scenarios that compare research- and market-driven strategies.

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**TABLE 1. The 26 Technologies Included in This Study**[a]

| major category | subcategory | major category | subcategory |
|---|---|---|---|
| 1. crystalline-Si | 1a. c-Si | 4. excitonic | 4a. organic, small molecule |
| | 1b. mc-Si, wafer-based | | 4b. organic, polymer |
| | 1c. mc-Si, ribbon or sheet | | 4c. dye-sensitized $TiO_2$ |
| | 1d. mc-Si, novel | | 4d. hybrid organic/inorganic |
| 2. thin-film | 2a. a-Si/multijunction a-Si | | 4e. quantum dot composite |
| | 2b. thin Si | 5. novel, high-efficiency | 5a. hot carrier |
| | 2c. CdTe | | 5b. multiple electron−hole pair |
| | 2d. CIS and related alloys | | 5c. multiband |
| | 2e. polycrystalline multijunction | | 5d. frequency up/down conversion |
| | 2f. novel materials | | 5e. plasmonics |
| 3. concentrator | 3a. c-Si, up to 100× | | 5f. thermophotovoltaics |
| | 3b. c-Si, 100−1000× | | |
| | 3c. III−V multijunction, up to 100× | | |
| | 3d. III−V multijunction, 100−1000× | | |
| | 3e. novel | | |

[a] Detailed definitions of each category were provided to the experts as needed and can be viewed in Appendix A of the full survey instrument (see Supporting Information).

**TABLE 2. The 18 Experts Who Participated in This Study**

| name | affiliation | name | affiliation |
|---|---|---|---|
| Barnett, Allen | University of Delaware | Merfeld, Danielle | GE Global Research |
| Green, Martin | University of New South Wales | Nozik, Arthur | NREL and U. of Colorado |
| Hambro, Chip | First Solar | Parkinson, Bruce | Colorado State University |
| Hammond, Troy | Plextronics | Rosey, Richard | Solar Power Industries |
| Hegedus, Steven | University of Delaware (IEC) | Shaheen, Sean | University of Denver[a] |
| Janssen, René | Eindhoven U. of Technology | Surek, Tom | Motech Americas[a] |
| Lewis, Nathan | Cal Institute of Technology | Swanson, Richard | SunPower |
| McCandless, Brian | University of Delaware (IEC) | Williams, Brown | Evergreen Solar |
| McConnell, Robert | NREL | Wohlgemuth, John | BP Solar |

[a] Formerly at NREL.

Experts were recruited from a group of 58 PV technology experts from industry, academia, and national laboratories, primarily NREL. All responses are anonymously reported. The study was conducted between April and September 2007. Initial responses were obtained via mailed surveys and/or electronically. Subsequently, 14 detailed surveys that used printed workbooks were completed via telephone or face-to-face interviews. When subsequent analysis revealed inconsistencies, experts had the option to make revisions.

We used a significant number of experts because we believed that there would likely be a wide range of opinions within the research community and we wanted a large enough group to reflect that diversity of views.

A detailed description of the survey and its development, a discussion of several issues related to the internal self-consistency of expert responses, and the survey instrument in its entirety can be found in the online Supporting Information.

## Results

**All Experts on All Technologies.** The assessed probabilities of each of the 26 PV technologies achieving the two price benchmarks in 2030 are reported in Figure 1 ($1.20/$W_p$ above, $0.30/$W_p$ below). Results for 2050 are reported in Figure 2. The diameter of each dot is proportional to the number of experts who gave each response, the smallest representing a single expert. All assessed probabilities have been binned in increments of 0.05.

For 2030, half-or more of the experts assess a better than even chance of achieving module prices of ≤$1.20/$W_p$ for all crystalline Si and thin-film technologies and for three of five concentrator technologies (Figure 1). Eight experts are virtually certain that CdTe devices will be ≤$1.20/$W_p$ by 2030.

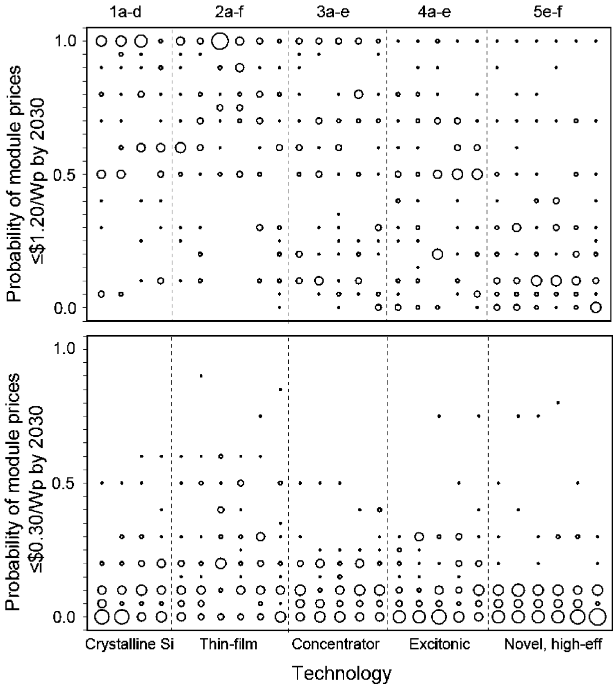

**FIGURE 1. Probability of achieving module prices of (top) $1.20/$W_p$ or less and (bottom) $0.30/$W_p$ or less by 2030. The results shown here are for all 26 current and emerging PV technologies and for all 18 experts, regardless of expertise level in a given technology. The circle diameter represents the number of experts who responded with the given probability for the given PV technology; the smallest circle corresponds to one expert, the largest corresponds to 8 in both graphs.**

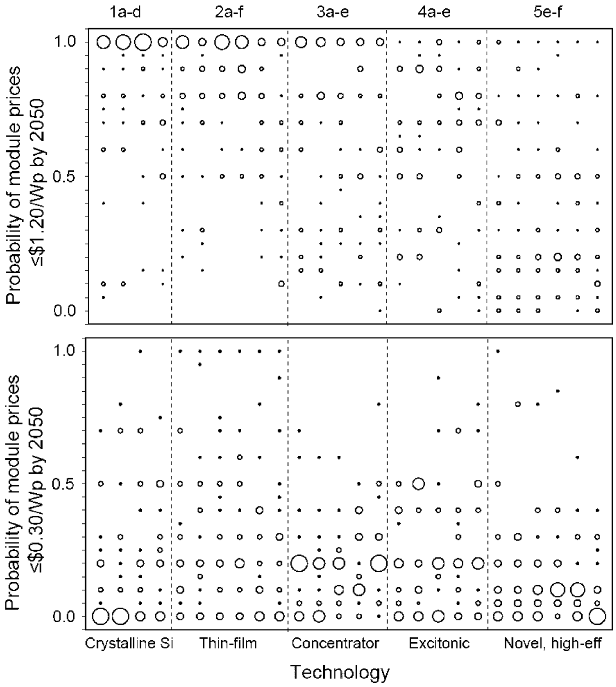

**FIGURE 2. Probability of achieving module prices of (top) \$1.20/W$_p$ or less and (bottom) \$0.30/W$_p$ or less by 2050. The results shown here are for all 26 current and emerging PV technologies and for all 18 experts, regardless of expertise level in a given technology. The circle diameter represents the number of experts who responded with the given probability for the given PV technology; the smallest circle corresponds to one expert, the largest in the top panel corresponds to 9, and the largest in the bottom panel corresponds to 7.**

At most, 2 of 18 report more than an even chance that a price of ≤\$0.30/W$_p$ will be met by any individual technology. Many experts believe that one or more individual technology has no chance of reaching this price.

The prospects of reaching both price thresholds improve for all technologies by 2050 (Figure 2). A few believe it is virtually certain some individual technologies will reach the price threshold of \$0.30/W$_p$. However, all report odds of ≥0.5 for a price of ≤\$1.20/W$_p$ for only two specific technologies, CdTe and CIGS.

Appropriately, several experts cautioned that the results of this survey should not be used to "pick winners" and noted the importance of a diversity of approaches. However, the experts themselves see several technologies as more likely to meet the \$1.20/W$_p$ price threshold in 2030, and there is little agreement on whether the \$0.30/W$_p$ threshold can be met, even by 2050. We note that Figures 1 and 2 do not reflect differences in other factors that determine LCOE, such as module lifetime.

Figure 3 reports the judgments of all experts that *any* PV technology, including one that is not specifically included herein, will achieve the four price-year benchmarks. All believe that with probability ≥0.70, PV module prices will be at or below \$1.20/W$_p$ by 2030. The majority say with complete confidence that this target will be met. As one expert put it, "a buck-twenty is easy." There is far less consensus about whether \$0.30/W$_p$ is achievable. In the words of the same expert, "under a buck is going to be hard." However, more than half of the experts assessed a probability of >0.50 that this target can be met by 2050. These probabilities mirror the responses presented above for the individual technologies. The apparent higher level of optimism reflects the fact that most experts gave at least one of the 26 technologies a relatively high probability of reaching the benchmarks.

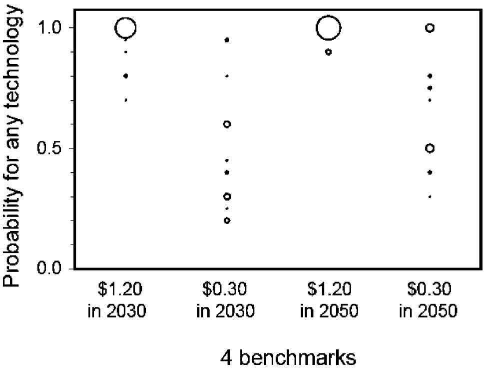

**FIGURE 3. Probability of any PV technology achieving 4 benchmarks. From left to right, benchmarks are as follows: module prices of \$1.20/W$_p$ or less by 2030; \$0.30/W$_p$ or less by 2030; module prices of \$1.20/W$_p$ or less by 2050; and \$0.30/W$_p$ or less by 2050. The circle diameter represents the number of experts who responded with the given probability for the given PV technology. A total of 18 experts responded. The smallest circle corresponds to one expert, and the largest two circles correspond to 13 experts in 2030 and 15 experts in 2050.**

To check for "motivational bias," we sorted the results from Figures 1 and 2 by self-ranked expertise. No clear trend is apparent as a function of expertise for any of the technologies (see Supporting Information Figures S1–S5).

**Selected Experts on Specific Technologies.** Fourteen experts evaluated one or more of the original 26 technologies in detail. Technologies were chosen based on a combination of high self-assessment of expertise and relatively high expectation of meeting the price thresholds in 2030. Expert judgments of the possible improvements for each technology indicated that significant further maturation is possible for all (Supporting Information Table S1).

Common themes emerged on barriers to large-scale commercial success for the major PV categories, and improved efficiency was mentioned for all. These themes are described in the Supporting Information, and the complete responses are compiled in Table S2.

Many experts displayed limited awareness of practical details of employing PV in power system applications, such as a lack of familiarity with the concept of capacity factor and its implications for developing commercially competitive bulk power systems (Supporting Information Table S2). Experts were largely in agreement on the expected lifetimes of the various PV categories (Supporting Information Table S2). Most expect at least 30 years of useful life for crystalline Si technologies; 20–30 years for thin-film technologies (one said 10–20 years); ~20–30 years for concentrator PV technologies; 10–15 years for excitonic material devices (but possibly longer with selective replacement of degradable components). Estimates for novel, high-efficiency devices were bimodal depending upon material: ~10 years or ~30 years.

After considering barriers to success and expected characteristics of the mature technology, experts were asked to provide ranges and best estimates of efficiencies and prices under the four policy scenarios. Figure 4 displays results for crystalline Si, thin-film, and excitonic technologies, which have moderate expected efficiencies. Figure 5 displays results for concentrator and novel, high-efficiency devices. Responses of a single expert under all four policy scenarios are grouped together (efficiency above, price below) and are separated from other expert responses by dashed lines. The total number of experts responding, the specific technology being evaluated, and the self-assessed expertise level are also indicated. Several experts thought that large-scale commercial failure (reported as "no device") was a plausible future outcome for some technologies.

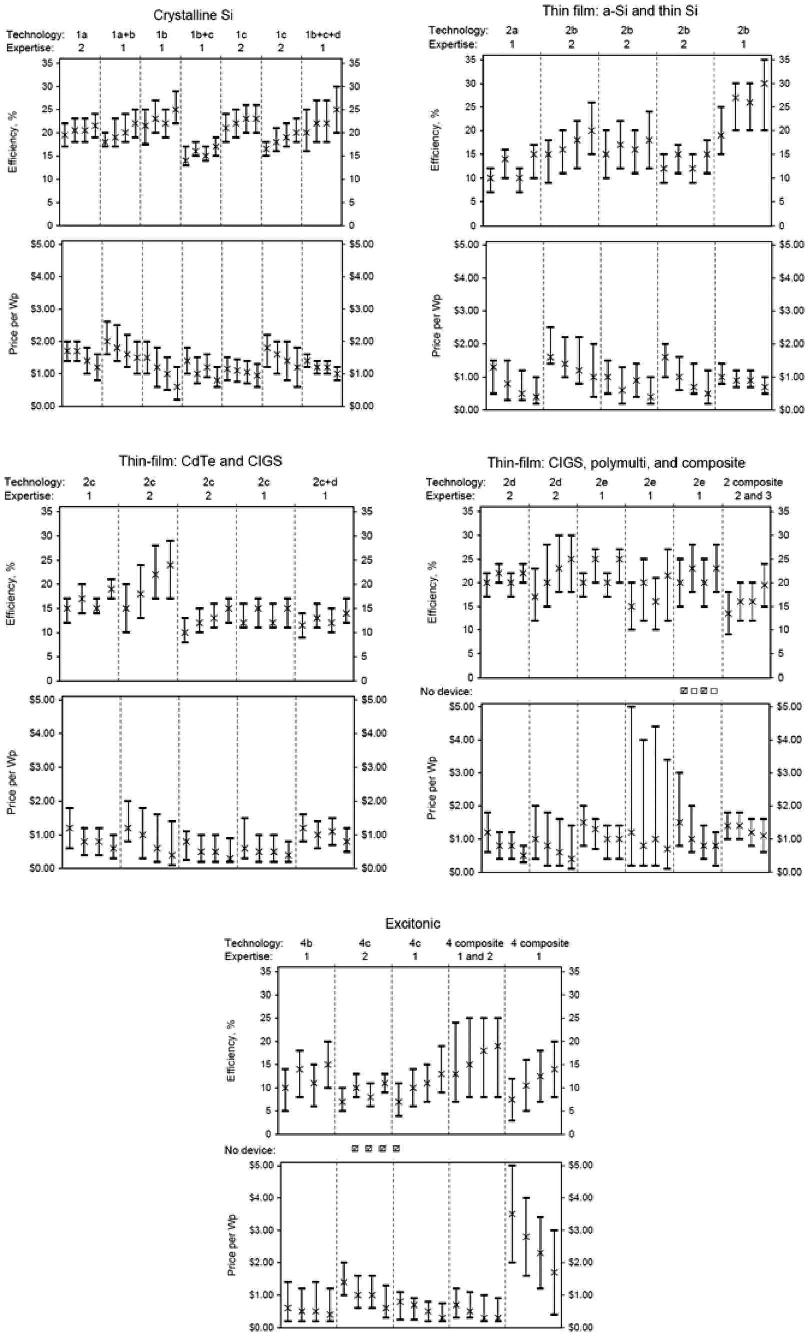

**FIGURE 4. Expert judgments of expected efficiencies and prices in 2030 for moderate-efficiency technologies. Each set of responses, separated by dotted lines, are those of a single expert under the four policy scenarios described in the text, ordered from left to right. The specific technologies evaluated and the expert's self-assessed expertise levels are listed across the top. (A) Crystalline Si (6 experts responding); (B) Thin-film: a-Si and thin Si (4 experts responding); (C) Thin-film: CdTe and CIGS (5 experts responding); (D) Thin-film: CIGS, polymulticrystalline, and composite (5 experts responding); and (E) Excitonic (5 experts responding).**

Estimated ranges for efficiencies and prices are broad. For example, for crystalline Si technologies, there is more than a factor of 2 difference between the most optimistic efficiency reported under the most aggressive policy scenario (the "highest maximum value" of 30%) and the most pessimistic efficiency reported under the least aggressive policy scenario (the "lowest minimum value" of 13%) (Figure 4, Table 3). Similarly broad ranges in efficiency were given for the other technologies (Figures 4 and 5, Table 3). The ranges of prices are even greater. For crystalline Si technologies, the most pessimistic plausible price under the least aggressive policy scenario ($2.60/$W_p$) is 13× the most optimistic price plausible under the most aggressive policy scenario ($0.20/$W_p$) (Figure 4, Table 4).

The best estimates for expected module prices in 2030 vary by more than a factor of 3 (Table 4). Note that the actual outcome may not be the average of all expert opinion, and a particular expert may have better technical information or better intuition in making probabilistic judgments. While we asked the experts to provide "absolute highest" and "absolute lowest," given the well-known tendency to overconfidence, and based on feedback from several experts, ranges reported ranges are probably closer to ~95% confidence intervals.

Historically, PV has followed a respectable experience curve with increasing capacity (*25*). However, recent work by Margolis suggests that even if these rates are maintained, it will be hard to achieve module prices near $1/$W_p$ by

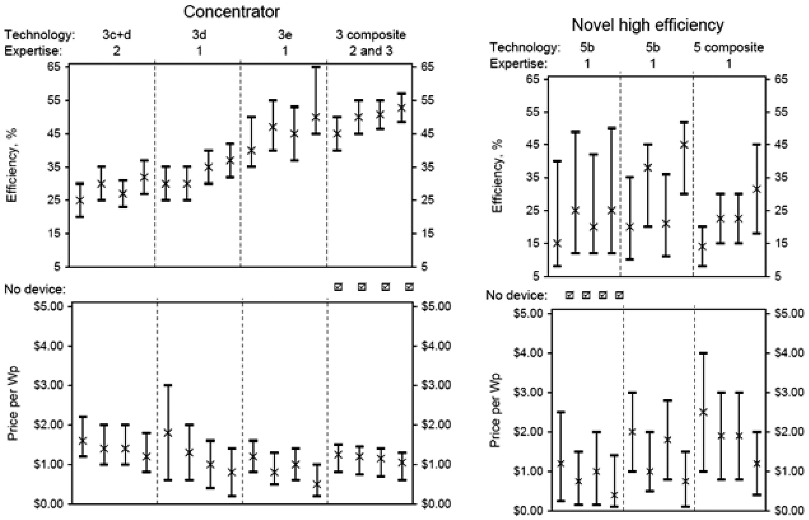

**FIGURE 5. Expert judgments of expected efficiencies and prices in 2030 for high-efficiency technologies. Display format is identical to that of Figure 4. (A) Concentrator (4 experts responding); and (B) Novel, high-efficiency (3 experts responding).**

**TABLE 3. Extremes in Estimated Percent Conversion Efficiencies**[a]

| technology | cryst. Si | thin film: 2a+b | thin film: 2c+d | thin film: 2d+e+ composite | conc. | excitonic | novel, high-efficiency |
|---|---|---|---|---|---|---|---|
| high max. value | 30 | 35 | 29 | 30 | 65 | 25 | 52 |
| high best estimate | 25 | 30 | 24 | 25 | 53 | 19 | 45 |
| low best estimate | 14 | 10 | 10 | 13 | 25 | 7 | 14 |
| low min. value | 13 | 7 | 8 | 9 | 20 | 3 | 8 |

[a] Each column lists the extreme values of judgment made by any expert under any policy scenario and corresponds to the individual graphs contained in Figures 4 and 5.

**TABLE 4. Extremes in Estimated Module Prices**[a]

| technology | cryst. Si | thin film: 2a+b | thin film: 2c+d | thin film: 2d+e+ composite | conc. | excitonic | novel, high-efficiency |
|---|---|---|---|---|---|---|---|
| high max. value | \$2.60 | \$2.50 | \$2.00 | \$5.00 (ND) | \$3.00 (ND) | \$5.00 (ND) | \$4.00 (ND) |
| high best estimate | \$2.00 | \$1.60 | \$1.20 | \$1.50 | \$1.80 | \$3.50 | \$2.50 |
| low best estimate | \$0.60 | \$0.40 | \$0.30 | \$0.40 | \$0.50 | \$0.30 | \$0.40 |
| low min. value | \$0.20 | \$0.20 | \$0.10 | \$0.10 | \$0.20 | \$0.20 | \$0.10 |

[a] Each column lists the extreme values of judgment made by any expert under any policy scenario and corresponds to the individual graphs contained in Figures 4 and 5. "ND" refers to "no device": for at least one technology in the group, i.e., at least one expert thought there was a possibility that the device would not be successful under at least one policy scenario.

expansion of production of the more mature crystalline-Si technologies (*26*). Additionally, the historic experience curve does a relatively poor job of predicting prices during the past decade, when prices have not decreased as expected while capacity has increased by nearly 10-fold. This may reflect the short-term result of Si supply and high demand, but it could also signal that the industry is transitioning to a lower learning rate as it matures. In either case, it seems likely that a new class of devices, which enables a discontinuous improvement at low cumulative capacities, will be needed to achieve prices below \$1/$W_p$.

Figures 4 and 5 indicate judgments of the relative effectiveness of R&D spending versus deployment incentives and provide insight on the choice between market support mechanisms that might drive learning-by-doing and investment in high-risk, high-payoff research. Table 5 reports separate comparisons of expected efficiency and of expected price between the status quo, the scenario that increases R&D spending by a factor of 10, and the one that increases deployment by a factor of 10. Note that the latter need not entail an order of magnitude increase in direct government spending for deployment, but includes any incentive(s) that would increase deployment by an order of magnitude (e.g., tax incentive, feed-in tariff, renewable portfolio standard with PV set-aside). However, the total cost to society (including expenditures by government, consumers, and utilities) would increase by an order of magnitude, even if costs, which have recently been climbing, resume their downward trend at historical rates. Considering the choice between the two policy mechanisms across all technologies, the experts indicate that promoting deployment will lead to the largest improvement in price. Of course, that is a statement about the future price trajectory of a specific technology. It does not imply that massive deployment of current generation technology will lead to more than gradual price reduction.

For all technologies except excitonic materials, the impact of R&D on efficiency is expected to be greater than that of expanded deployment. Since the price of power in \$/$W_p$ depends on both efficiency and cost per unit area, focusing on efficiency may not be the most effective way to bring a

**TABLE 5. Number of Experts Who Judged Each of The Policy Options To Be Most Important for Different Groups of Technologies**[a]

| technology | dominant policy mechanism for efficiency: R&D | dominant policy mechanism for efficiency: deploy | dominant policy mechanism for efficiency: same | dominant policy mechanism for price: R&D | dominant policy mechanism for price: deploy | dominant policy mechanism for price: same |
|---|---|---|---|---|---|---|
| crystalline Si | 2 | 3 | 2 | 1 | **5** | 1 |
| thin film: 2a+b | **4** | 1 | 0 | 1 | **3** | 1 |
| thin film: 2c+d | **3** | 2 | 0 | 1 | 2 | 2 |
| thin film: 2d+e+ composite | **4** | 1 | 1 | 1 | **4** | 1 |
| concentrator | 2 | 2 | 0 | 1 | 2 | 1 |
| excitonic | 2 | **3** | 0 | 1 | **3** | 1 |
| novel, high-efficiency | **2** | 0 | 1 | **2** | 0 | 1 |

[a] For each set of technologies (as grouped in Figures 4 and 5), the number of experts who indicated that one of the two policy mechanisms (10 × increase in R&D or 10 × increase in deployment) would be more effective at improving efficiency or price are tallied under "R&D" or "Deploy" (for deployment). In cases where there is an overall dominant policy mechanism (i.e., a majority of experts believe it is most effective for a given group of technologies and a given metric), the total is in boldface font. Experts who thought the impact of the two increases would be the same are reported under "same."

PV technology into large-scale commercial use. One reading of these results is that R&D may produce efficiency improvements associated with cost increases that could offset much of the benefit.

At the same time, research is often less expensive than deployment incentives in absolute terms. Although we did not define specific dollar amounts in our elicitation for either of the policy mechanisms, an order-of-magnitude comparison of the two is illustrative. Annual DOE investments in PV R&D are roughly \$150 million, based on the FY08 budget of \$138 million in DOE/EERE for "PV energy systems" and the ~\$23 million in DOE's Basic Energy Science program, which is broadly aimed at "solar technologies," including solar thermal. U.S. sales of PV in 2005 were roughly \$725 million (*27*), or ~\$1.4 billion, assuming a 50:50 breakdown of module: BOS costs. Thus, increasing deployment by a factor of 10 would cost society around \$14 billion, while increasing R&D investment by a factor of 10 will cost roughly 10% as much. Even if learning produces cost reductions faster than expected and deployment costs are consequently lower than predicted, absent some dramatic break through resulting from research, the cost differential will remain large because PV is as much as an order of magnitude more expensive than other low-carbon options. Given this, and given the very mixed views of our respondents about the relative effectiveness of expanded R&D versus expanded deployment, policy makers should think very carefully before endorsing a deployment-based strategy as a vehicle to reduce PV costs if the goal is bulk low-carbon electricity supply.

We asked experts six open-ended discussion questions. A complete list of all expert responses to these, and a compilation of other notable remarks, can be found in the Supporting Information. We note here that while most experts expected ~50% of total system costs to be attributable to BOS, many appeared to have limited first-hand knowledge of BOS costs.

## Discussion

Emerging technologies, such as those classified herein as "excitonic" and "novel, high efficiency", are often mentioned anecdotally as contenders for revolutionary breakthroughs. There is little agreement among the experts in this study about the probability of this happening. Taken as a whole, our results suggest that if PV prices fall to $\leq$\$0.30/$W_p$ by 2050, it is as likely to be achieved with mature technology as with emerging technology, and neither is guaranteed. Our confidence in this finding is strengthened by the fact that we find no indication of systematic bias of experts for or against their "own" technologies. Beyond these few basic findings, the opinions of our experts vary widely.

Many experts apparently started with a base assumption that both R&D and support for expanded deployment will increase by even more than our "×10" policy options and many stressed the importance of expanded deployment. But as one expert noted "deployment money keeps interest going in the short term to achieve retail parity and peak shaving benefits, but R&D is important in the long term." Experts were more focused on research and manufacturing issues, rather than those associated with large-scale deployment.

**Electricity Cost Comparison.** With future capital prices of \$1.20 and \$0.30/$W_p$, and assuming a module lifetime of 25 years and no decrease in power output over that period, a capacity factor of 15%, a 12% capital charge rate, annual maintenance of 0.5% of the capital cost, and balance of system costs equal to the cost of the modules, and ignoring any intermittency charge, the cost of delivered bulk electricity will be ~\$240 and ~\$60/MWh, respectively.

With different assumptions, different results can be obtained. For example, if progress in power electronics lowers BOS costs, electricity price will decrease. However, when estimated as a percentage of total system costs, lower BOS prices are more plausible for the higher benchmark price. At \$0.30/$W_p$, BOS costs lower than 50% is an aggressive assumption. Increases in module lifetime have marginal impact on the price of electricity; for example, increasing the lifetime under the higher module benchmark price to 80 years decreases delivered electricity costs to \$230/MWh. Increasing capacity factor to 19%, that observed under arguably ideal climate conditions in Arizona with a 4.6 MW utility system over two years (*3*), decreases the costs to \$190 and \$50/MWh for the high- and low-benchmark prices, respectively. While some LCOE estimates include tax breaks and rate subsidies, we exclude them to achieve an unsubsidized comparison with other technologies. The most significant sensitivity is to the capital charge rate. Lowering this value to 10% lowers the price of delivered electricity to \$210 and \$50/MWh for the high- and low-benchmark prices, respectively; a 5% capital charge rate yields \$140 and \$35/MWh. Given the societal value of addressing climate change and reducing dependence on imported fuels, a case might be made for socially subsidized capital charge rates that are below commercial rates. However, such rates would also logically apply to other low-carbon technologies, negating the effect of this sensitivity relative to other options.

It is sometimes argued that the shape of the diurnal output of PV matches diurnal energy needs. However, utility load curves, and associated marginal prices for power, can peak during periods when there is little or no sun (see, for example, Figure S6). Note too that wind has a somewhat higher capacity factor, and blows both day and night, although no cost advantage for this difference has been included in our comparison.

Using our initial assumptions and a current cost of \$5/$\mathrm{W_p}$, PV electricity costs are \$500/MWh. The U.S. Department of Energy reports that the capacity weighted cost of electricity from wind was \$35/MWh in 2006 (*10*). A recent analysis by Harding that considers rapidly rising material costs as well as O&M, estimates a cost for wind of \$70/MWh (*12*). It should be noted that these figures do not include any additional expense of addressing the intermittency of PV and wind. In 2005 the IPCC estimated the cost of electricity from natural gas plants with carbon capture and storage (CCS) at between \$43 and \$77/MWh and from IGCC coal plants with CCS at between \$51 and \$91/MWh (*13*). A 2003 MIT study of nuclear power estimated current costs of electricity from new nuclear power at \$67$_{2002}$/MWh (*28*). Harding's more recent analysis yields cost of the order of \$90/MWh. EPRI has estimated that a combination of advanced technologies should be able to supply electricity at ≤ 65\$$_{2007}$/MWh by 2050 (*29, 30*). Taken as a whole, these figures indicate that the lower of the future price thresholds in this elicitation is appropriate.

PV can also be deployed on rooftops or in building-integrated systems. Average retail rates in the U.S. today are about 11¢/kWh and were 12.4, 17.5, and 26.1¢/kWh in CA, NY, and HI, respectively, in October 2007 (*31*). At 24¢/kWh in 2030 (i.e., the higher of the two price thresholds), PV could become comparable with retail rates in regions that have very high costs for grid-supplied electricity and have fully internalized the costs of central generation (*32*). Evaluating the tradeoffs with advanced efficiency in such settings would require assessment that we have not performed. Additionally, while the economies of scale possible with centralized PV might dominate pure economic considerations for PV deployment, other noneconomic factors (including "green status") will likely drive the rooftop and building integrated markets outside of the developing world. However, both distributed and centralized PV at any significant scale will impose costs on electric utilities, which we have not included, in order to deal with intermittency and the timing mismatch between utility load curves and solar output.

Given these factors, the low probabilities that many experts assess of meeting a price of \$0.30/$\mathrm{W_p}$ by 2050, and the wide dispersion in their assessments of efficiencies and prices, we conclude that PV may have difficulty becoming economically competitive with other large-scale, low-carbon bulk electricity options in the next 40 years. At the same time, it seems likely that PV will continue to expand into a variety of smaller-scale markets. Of course, past efforts to make technical and energy-related predictions have often missed the mark (*33, 34*). Unanticipated technical developments could similarly overturn the judgments herein, but before R&D reduces uncertainties, massively subsidized deployment of existing technology is arguably not the best way to increase the odds of such an outcome.

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## Supporting Information Available

Supplemental Methods discussion; expert responses sorted by expertise (5 Figures, S1−S5); expert judgments of the possible improvements for PV technologies (Table S1); expert assessment of barriers to large-scale commercial success (Table S2); a complete list of all expert responses to the six Discussion Questions; a compilation of other notable remarks by the experts; and an example of the mismatch between PV output and utility load (Figure S6). The survey instrument is also provided. This information is available free of charge via the Internet at http://pubs.acs.org.

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