Expert Assessments of Future Photovoltaic Technologies

Supporting Online Information

AIMEE E. CURTRIGHT[*†‡], M. GRANGER MORGAN[†], AND DAVID W. KEITH[§]

Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213 USA and Energy and Environmental Systems Group, University of Calgary, Calgary, Alberta, Canada, T2N 1N4

Number of pages: 23

Number of Figures: 6

Number of Tables: 3

[*] Corresponding author email: aimee_curtright@rand.org; phone: 412-683-2300 x4989; fax: 412-683-2800
[†] Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213 USA
[‡] Present address: RAND Corporation, 4570 Fifth Avenue, Pittsburgh, PA 15213 USA
[§] Energy and Environmental Systems Group, University of Calgary, Calgary, Alberta, Canada, T2N 1N4

Methods

Description of survey. Participants were asked to rank their own level of expertise in all twenty-six PV technologies on an eight point scale. These were binned into four groups, 1 corresponding to the top two levels of expertise and 4 the lowest two levels.

The detailed portion of the survey used a protocol similar to those employed in other recent elicitations (19-22). For each of the individual technologies, experts were asked to:

1) Assess the maturity, list the most important technical barriers to success, and give some expected characteristics of the mature technology;
2) Estimate ranges (maximum and minimum values) and then give best estimates for module efficiencies in 2030 under four policy scenarios; and
3) Estimate ranges and then give best estimates for module prices in 2030 under the same four policy scenarios.

The four policy scenarios were:

Status quo: Current government R&D funding levels for the PV technology being considered and current government incentive levels for deployment of PV technologies in general,

Enhanced R&D (by 10×): 10 times the current government R&D funding levels for the PV technology being considered and current government incentive levels for deployment of PV technologies in general,

Enhanced deployment (by 10×): Current government R&D funding levels for this PV technology and 10 times increased government incentive levels for deployment of PV technologies in general,

Enhanced R&D and deployment (both by10×): Both 10 times the current government R&D funding levels for this PV technology and 10 times increased government incentive levels for deployment of PV technologies in general.

A detailed appendix provided further clarification of these scenarios (see Appendix C in the survey, available in Supporting Information). Finally, experts were asked to comment on six open-ended "Discussion Questions" relevant to the technical and economic success of PV.

Experts were asked to consider the barriers to future large-scale commercial success in three areas: (1) basic R&D; (2) engineering and applied R&D; and (3) manufacturing. They ranked the importance of each area, from "Without substantial advances, this technology will not be developed" to "Device development can go forward now but advances would be helpful" to "Current status is excellent." Experts were then asked to list the "3-5 most important overall advances necessary for the large-scale commercial success" of the technology. After considering barriers to success, the experts then provided ranges and best estimates for efficiency and price in 2030 (items 2 and 3 above) assuming the commercial success of the device, especially when considering its use for large-scale power generation applications. Since a device might not be successful in this time frame, experts were given the option of indicating "No device" as the worst case scenario. Finally, experts were asked to comment on six open-ended "Discussion Questions" relevant to the technical and economic success of PV.

Development of the survey. The interview protocol was revised in response to feedback during piloting and, to a lesser extent, early interviews. For example, the survey initially did not include BOS because we understood this to be relatively independent of specific PV technology. Several experts argued that BOS costs could be module-technology specific or might, for example, differ substantially when comparing roof-top to utility-scale PV. Accordingly, we asked experts to comment on BOS as part of the "Discussion Questions." Also, pilot surveys included fewer technology categories, clustering many of the twenty-six specific technologies. We elaborated the technologies in the final version because the tradeoffs between (area-related) cost and efficiency can be highly technology specific and because we wanted to avoid "picking winners."

Problems of internal consistency. A few experts gave a lower probability for the success of any PV technology than they had given for the highest individual probability under the same benchmark conditions. When the problem was noted, experts readily corrected their responses. However, most other experts estimated the probability of *any* technology reaching a given benchmark as equal to or only slightly larger than the largest individual probability for the same benchmark. Unless there is high correlation for success across the technologies, the probability that *any* technology will reach a benchmark should be higher than that for any individual technology.

Several experts estimated identical probabilities that an individual technology would reach the two price thresholds in a given benchmark year, and many gave a relatively high probability for the lower price threshold (e.g. ~50%) and a probability for the higher benchmark that was less than 100%. While there are conditions in which such answers could be obtained, we asked experts to clarify their intentions, and in most cases they made adjustments.

Furthermore, when we compared expert responses in the earlier portion of the survey (the values summarized in Figs. 1 and 2) to those given in the later detailed portion of the survey, all but one expert was more optimistic in the first response mode than they were in the latter under the status quo scenario. In well over half of the initial assessments, values were more optimistic than even the most aggressive policy scenario, several dramatically so. The majority of the remaining initial responses were only self-consistent when compared with the price ranges given for the most aggressive policy scenario. We originally assumed that most experts would be thinking of a status quo-like scenario when giving their initial probabilities for all technologies. Only three experts explicitly inquired about the "state of the world" or asked for policy assumptions before filling out the values in the matrix. However, most appear to have assumed that future funding for R&D and/or deployment will be substantially more aggressive than in recent history, and made their initial judgments accordingly.

After discussing these inconsistencies, most experts chose to revise their responses, usually lowering the price ranges, especially the lower bound, given in the detailed portion. However, some lowered the probabilities given in their initial estimates, and some changed both sets of estimates. Only two experts opted to keep their exact original responses. One expert explicitly expressed the opinion that PV policy would be even more aggressive than our most aggressive scenario. Several explained that their ranges reflected something more like 90% or 95% confidence intervals. One of these experts commented that it would be "meaningless" to give an absolute range because that would extend from $\$0/W_p$ to no change from today's price. Finally, one expert commented that, in the initial assessment, "all scenarios are possible," noting that explicitly defining the policy scenarios in the latter, detailed assessment limited the possible outcomes in their mind and decreased optimism in the prospects for the technologies.

Results

Expert responses sorted by expertise.

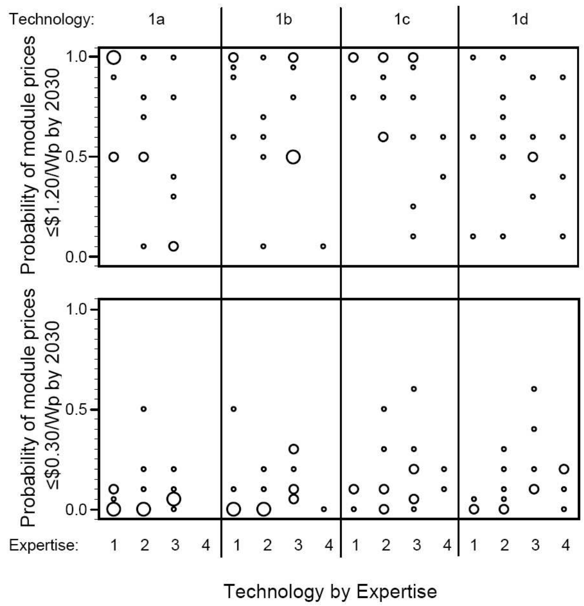


FIGURE S1. Responses sorted by expertise level: Probability of crystalline Si technologies achieving module costs of (top) \$1.20/W_p or less and (bottom) \$0.30/W_p or less by 2030. The responses for all experts have been sorted by the experts' self reported level of expertise, where 1 corresponds to the highest level of expertise and 4 corresponds to the lowest level of expertise. From the absence of any systematic pattern, we conclude that "motivational bias" was not a serious problem.

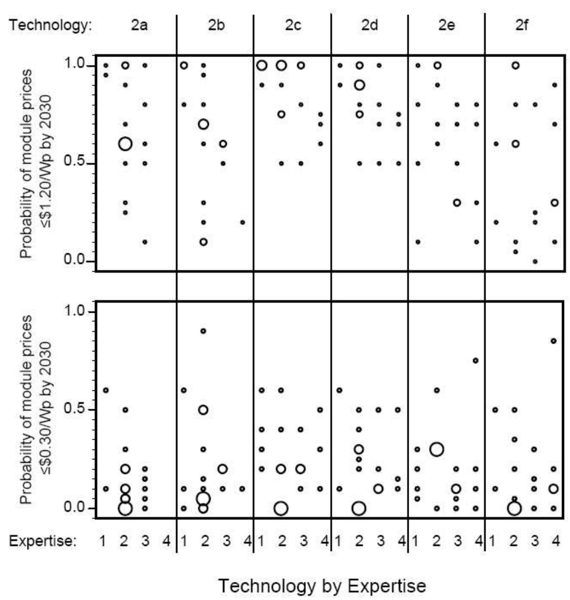


FIGURE S2. Responses sorted by expertise level: Probability of thin-film technologies achieving module costs of (top) \$1.20/W_p or less and (bottom) \$0.30/W_p or less by 2030. The responses for all experts have been sorted by the experts' self reported level of expertise, where 1 corresponds to the highest level of expertise and 4 corresponds to the lowest level of expertise.

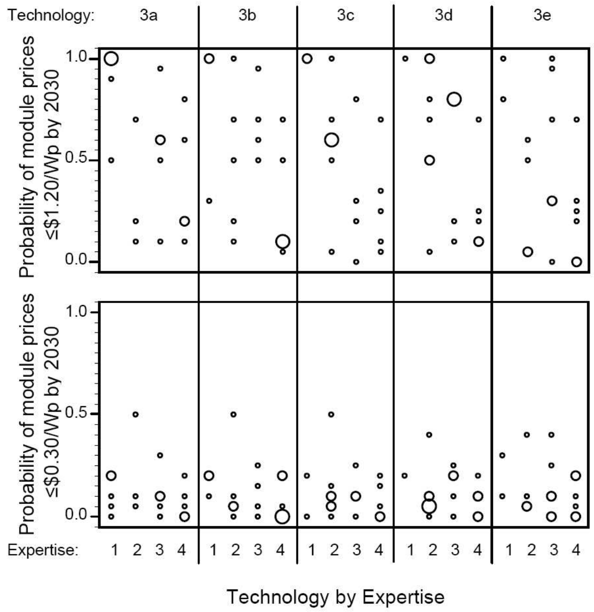


FIGURE S3. Responses sorted by expertise level: Probability of concentrator technologies achieving module costs of (top) \$1.20/W_p or less and (bottom) \$0.30/W_p or less by 2030. The responses for all experts have been sorted by the experts' self reported level of expertise, where 1 corresponds to the highest level of expertise and 4 corresponds to the lowest level of expertise.

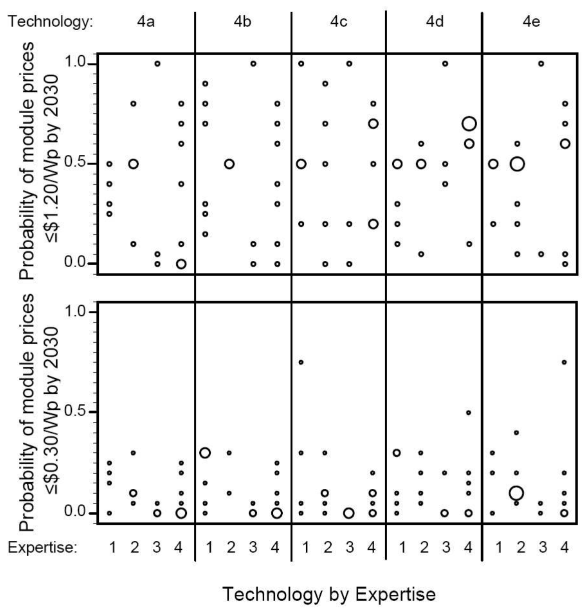


FIGURE S4. Responses sorted by expertise level: Probability of excitonic technologies achieving module costs of (top) \$1.20/W_p or less and (bottom) \$0.30/W_p or less by 2030. The responses for all experts have been sorted by the experts' self reported level of expertise, where 1 corresponds to the highest level of expertise and 4 corresponds to the lowest level of expertise.

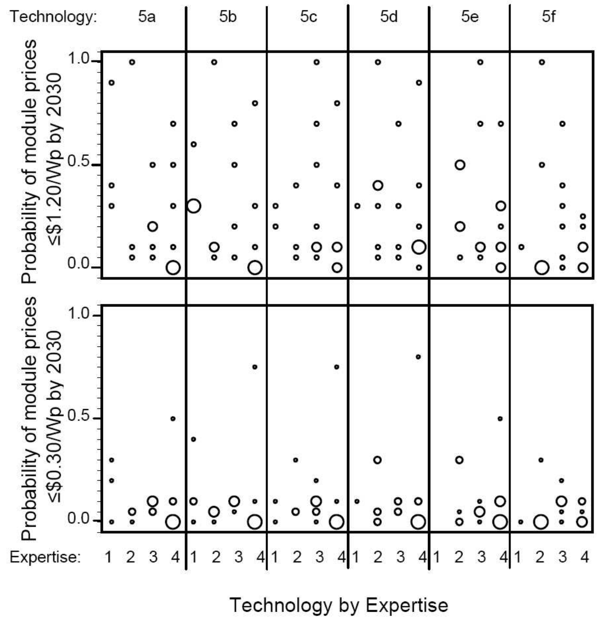


FIGURE S5. Responses sorted by expertise level: Probability of novel, high-efficiency technologies achieving module costs of (top) $1.20/$W_p$ or less and (bottom) $0.30/$W_p$ or less by 2030. The responses for all experts have been sorted by the experts' self reported level of expertise, where 1 corresponds to the highest level of expertise and 4 corresponds to the lowest level of expertise.

Table S1. Judgments of the Level of Maturity of Each Technology in Each of Three Major Areas of R&D[a]

Technology	Type of R&D/Experience	Maturity				
		Least		Mid		Most
Crystalline Si	Basic		1	5	1	
(N=7)	Engineering/Applied		3	2	2	
	Manufacturing		2	4	1	
Thin-film	Basic	4	7	5		
(N=16)	Engineering/Applied	3	8	5		
	Manufacturing	6 (1)[b]	4 (1)[b]	3	1	
Concentrator	Basic	1	1	2		
(N= 4)	Engineering/Applied	1	3			
	Manufacturing	2	1	1		
Excitonic	Basic	2	2	1		
(N= 5)	Engineering/Applied	3	2			
	Manufacturing	2	1		2	
Novel, high-efficiency	Basic	3				
(N= 3)	Engineering/Applied	2		1		
	Manufacturing	2			1	

[a]The number in each column indicates how many experts selected the particular level of maturity for a single sub-category or composite evaluation. For example, if a single expert evaluated multiple thin-film technologies separately, the maturity level in each category of R&D was tallied separately for each of these technologies. If an expert evaluated several sub-categories as a single “composite” technology, only a single ranking was tallied in each category of R&D. N is the number of experts responding in each case.

[b]Two experts marked their responses between the given defined maturity levels, but closer to one of the two. Their responses are tallied in parenthesis in the level to which their marks were closest.

Common themes on barriers to large-scale commercial success. All experts listed "thinner" and/or "cheaper" Si as one of the most important advances for crystalline Si technologies. Manufacturing improvements in handling, throughput, and yield were commonly mentioned. Improved packaging and reliability were high on the list for thin-film devices, as were improvements in process control, deposition rates, throughput and materials optimization (both the amount of material and material performance.) Thermal management and improved optics were unique issues cited for concentrator PV. More fundamental concerns, such as increasing open circuit voltage and understanding the nature of the exciton and exciton extraction, in addition to the above noted engineering and manufacturing issues, were cited for excitonic and novel high-efficiency PV. Improved efficiency was mentioned for all. Complete responses are compiled in Table S2.

Table S2. Most Important Barriers to Success and Characteristics of Mature Technology[a]

Technology	Most important overall advances	Capacity factor	Lifetime
	Crystalline Si		
1a.	• Thinner wafers • Higher Efficiency • Lower cost manufacturing plants	22-29% (range for resource)	30 years
1a+b.	• Polycrystalline feedstock Si price reduction/availability • Thinner wafers and related material handling of these wafers to maintain high process yields • Improved silicon wafer parameters, i.e. high lifetime mtl • Improved surface treatment, i.e. AR coating, texturing, to enhance conversion eff	25%	30 yrs (to 80% rated)
1b.	• Silicon feedstock from metallurgical grade Si. • Throughput and handling (1000 cells per hr vs. 1000 cells per min). • Taking lab efficiency to commercial production.	Small increase in energy rating possible (optics, cooling)	40-50 yrs
1b+c.	• Very thin wafers/ribbons • Processing thin wafers • Defect engineering/passivation • Manufacturing yield	25-27%	>25 yrs
1c.	• Control defects [in "cheap" materials]	0.2 [Similar to	Infinite

	• Parallel processing [automation/handling/large area processes more like thin-film] • Less material [glass → polymer]	today]	
1c (2nd)	• Increased throughput of ribbon production (multiple pulls, larger/wider ribbon) • Improved material (Si ribbon) quality • Continued reduction in ribbon thickness	25%	30 yrs
1b+c+d	• [Lower cost Si • Higher performance]	[0.19 (including low resource)]	[50 yrs (25 yr warrantee is half-life = 50)]
	Thin-film		
2a.	• Increased growth rate of nc-Si bottom cell • Increase eff[ciency] of multijuntion ~10% • Increase material utilization efficiency > 50%	24% (assuming c-Si is 20%)	>25 yrs
2b.	• Si material source enabled (low cost, high volume) • Si utilization • Wafer handling: automation for high throughput	20%	30 years
2b. (2nd)	• Need to develop methodology for film deposition • How to process “low quality films” to get reasonable efficiency • Packaging/reliability	No change	20-30 yrs
2b. (3rd)	• Front and back surface passivation • Grain boundary passivation • Light trapping • Fast recrystallization	0.20 (same as c-Si)	25 yrs (same as c-Si)
2b. (4th)	• [*Device* R&D “across the board” (i.e. from basic to manufacturing)]	NR	NR
2c.	• Open circuit voltage, fill factor limitations • Packaging costs need to drop • Number of processing steps need to be reduced	25%	>20 yrs
2c. (2nd)	• Module reliability/lifetime (packaging) • Throughput (manufacturing) • Materials optimization (to achieve higher efficiency) • Process control for large scale manufacturing	25%	~30 years
2c. (3rd)	• Optimization of efficiency • Scale-up of production • Convincing consumers of the safety of Cd/Te	Same as flat-plate	30+ years
2c (4th)	• Show path for increase efficiency to 12-14% in manufactured modules,	18%	>20 yrs

	not champion cell • Educate public about relative non-toxicity of CdTe: it has a perception problem not a real problem. • Identify why V_{oc} is so low relative to the CdTe bandgap – is it defects or device design?		
2c+d.	• Reduced thickness (several μm to <0.5 μm) • Device structures (CO, stable contacts) • Yield and throughput • Process development (compatible)	~25%	20-25 yrs
2d.	• Implementation of scalable CIGS deposition and junction formation processes • Development of new junction partners • Development of low-temp CIGS deposition process	25%	>20 yrs
2d. (2^{nd})	• Removal of Cd in layer (CdS layer) → EHS concerns • Module lifetime/packaging • Large-scale manufacturing	25%	30 years
2e.	• Understanding aspects of monolithic integration • Optical modeling and coupling(?) schemes • Defining interconnects and wiring schemes to utilize/optimize electrical harvesting from top/bottom cells	20%	> 20 yrs
2e. (2^{nd})	• [Monolithic – truly roll to roll • Uniformity/materials control (i.e. 80% of champion) • Throughput/scalability: Intel vs. Wall Street Journal]	[Similar to others]	[50 years]
2e. (3^{rd})	• High transparency top cell (let 95% light into bottom cell) • High efficiency top cell (>15% at E_g > 1.6 eV • Thermal compatibility of entire stacked device	Same as c-Si – 20%	20 yrs
2 composite	• Lower cost manufacturing plants • [Faster deposition rates (x10)] • Improved reliability and durability (TCO)	22-29% (depends on solar resource)	10-20 yrs
	Concentrator		
3c+d.	• Cell yield and cost • Packaging (materials thermal management, contacting) • Reliability (cell to tracking) • Manufacturing advances (tracking, packaging)	??	>20 yrs
3d.	• Improved optical efficiency • Redesign for less steel usage • Higher efficiency, low cost solar cells	25-29% (range for resource; tracking assumed)	30 yrs
3e.	• Device development, efficiency • Conc systems development	0.18	20-30 yrs

3 composite	• Cheap 50-60% cells • Long-lived, passive concentrator [e.g. 2D light pipe]	??	20+ years
	Excitonic		
4b.	• Stable interfaces of active layer w/electrodes • Low cost solution processable anode & cathode materials (no ITO; no vacuum deposition) • Low cost encapsulation (O_2, H_2O barrier) • Efficiency improvements • Translation to high percent of “lab performance” to scale	10-20% better than x-Si	10-15 yrs (by 2015)
4c.	• Efficiency and yield • Scale-up • Reliability	Standard flat plate, thin-film	~10 yrs
4c.	• Increase open circuit voltage • Increase spectral coverage • Verify long-term stability • Increase dye-absorbance (thinner cells) • Improve electrolytes	Standard flat-plate, thin-film (or slightly better)	15-20 yrs (replace dye/ solution?)
4 composite	• Identify “final” material sets • Identify degradation mechanisms • Nature of “exciton”	Mid-20s	10 years (viable at 5 years)
4 composite	• Getting excitons converted to charge carriers • Conducting charges to electrodes	22-29%	~10 years
	Novel, high-efficiency		
5b.	• Fundamental understanding of exciton extraction • Discovery of viable materials (Pb OK? Se OK?) • Cost? High-yield synthesis? • Scale-up	Standard flat plate, thin-film	5-10 yrs OR 25-30 yrs (depends on material)
5b. (2^{nd})	• Efficient exciton dissociation and e^- and h^+ separation and collection with very high efficiency (approaching 100%) so that the QY for photocurrent approaches that for the QY of exciton formation in the individual QDs • Move the threshold photon energy for MEG to $2xE_g$ (HOMO-LUMO) • The QY vs. photon energy characteristic needs to become step-like (very sharp rise in photocurrent after the threshold).	Same as other flat plate PV	Same as Si
5 composite	• Reduce substrate usage and cost • Extracting charge carriers • Understanding conversion processes	25-29% (range for resource)	30 years

[a]Responses are direct transcriptions of actual written comments unless contained within square brackets, which indicates non-written comments from interview conversation; within these, direct quotes are indicated as such. Unless otherwise noted, a specific number for the capacity factor was meant to imply "comparable to today's devices of same type." As evidenced by the responses above, experts generally felt this number was 20% or greater. However, recent work by Curtright and Apt (3) has indicated that this number is ~19% in sunny locations.

Discussion Questions

General themes. The first question was "What technological improvements would benefit multiple PV technologies?" Possible synergies mentioned involved packaging and encapsulation, interconnects and transparent conducting oxides (TCOs), and processing and manufacturing. Inverter improvements (lifetime and efficiency) were also cited. Question two was "What other industries or fields of research might provide advances or knowledge that might 'spill over' to PV?" Those mentioned more than once included flat panel displays, robotics, light emitting diodes (LEDs)/solid state lighting (SSL), semiconductors/digital electronics, chemical refining/improved chemistry, and thin-film material applications (deposition and handling). Question six was: "What do you expect in terms of balance of system improvements and prices? What percentage of total system prices will BOS constitute in 2030? In 2050?" The lowest BOS fractions of total cost given were 20% in 2030 and 10% in 2050 (by one expert), and the highest were 50-75% in any future year (again, one expert's response). Most values were in the range of 30-70%, with 50% the most common single response. No expert commented specifically on the type of module they were considering or whether or not they were thinking of roof-top or utility-scale installations. Experts seemed to feel that inverters have not yet been optimized for this application and that normal experience curves will be followed with cumulative capacity of PV, and no expert seemed to be concerned that this would be a stumbling block for PV. However, many experts appeared to have limited first-hand knowledge of balance of system costs.

Complete Responses to Discussion Questions. Below are the compiled results of expert written comments. Any clarifications or additional comments based on the live interview are in square brackets []; within these, direct quotes are indicated as such.

Q1. What technological improvements would benefit multiple PV technologies?

Module encapsulation

Light trapping

Interconnection and monolithic integration with narrow (< 100 μm) dead zones.

[TCOs [transparent conducting oxides) (material availability, compatibility/processing, p-type/transparent (multijunction), wider band gap)

Packaging (resist H_20, 0_2, UV; low cost)]

Si materials development (low cost materials development) [solar grade, not microelectronics methods]

Encapsulation technologies for flexible thin film [thin-films and novels]

TCOs?

Packaging?

[Manufacturing and BOS]

Physical characterization?[e.g. buried interfaces characterization]

Improvements in thin-film processing techniques

[Concentration for all: optics, non-tracking concentrators, 1000× and up.]

Inverter lifetime and efficiency improvements

Technology to reduce heat load

[Interconnection to the grid, house: tech is there; BOS]

Lower cost UV-resistance encapsulation

More user-friendly module mounting (plug-n-play)

Higher efficiency, efficiency, efficiency

Durability and reliability in operation

[Faster production rates (lower capital costs)]

[Encapsulation: non-glass, non-Al – right now needs lots of materials due to distributed resource – need long-lived, transparent rigid polymers/encapsulation systems]

Basic polycrystalline Si price reductions (technology and economies of scale)

Q2: What other industries or fields of research might provide advances or knowledge that might "spill over" to PV?

Robotics
Batteries!
Inverters
Chemical refined

[Semiconductor (progress goes both ways: semiconductors will benefit PV, vice versa)
Automation/robotics]

Displays & microelectronics (vacuum deposition, [other equipment], material handling in process)
Printing (roll to roll manufacturing, ink-jet "writing," [digital printing])

LEDs [light emitting diodes] and SSL [solid state lighting]
Nano/molecular research

Display industry has experience with thin-film processing of now larger and larger areas

[Chemistry hasn't met its potential: materials/solid state physics]

Production technologies from flat panel displays (for thin-film) and maybe CD's etc for wafers.

[Semiconductors, displays, all types of digital electronics]

Thin Si or a-Si have large overlap w/display + flat panel technology, can benefit from investment + tech gains in those areas.

History of wind energy development will be invaluable for concentrator PV development

[Biological systems spilling over into PV]

Semiconductor processing – thin-film material applications

Q3: What impact will building-integrated vs. utility-scale PV deployment have on technology viability?

Building integration will remain a novelty for next 10 yrs but may become prevalent as flexible cells are integrated into construction materials.
Utility-scale can have immediate impact by reducing peak load on solar farms from E. Coast to W. Coast

Not “viability” – just different sides of the utility meter (retail v. wholesale)

[BI=thin-film, utility-scale=concentrator]

I think that both will drive the development of PV but different technologies may be favored by the two sectors.

Concentrator suited for utility scale but not building integrated
Flat plate better suited for building integrated.

[Rooftops most important because retail/point-of-use; enough appropriate rooftops to provide 30% of electricity]

BIPV plays to strengths of thin film; Rooftop residential favors high eff[iency]; Utility scale summer peaking matches better high temperature perf. of a-Si or CdTe <u>vs</u> c-Si

Little impact. BIPV will be useful niche market for flat panel PV. Utility-scale market is TW-size market having larger impact

[Big solar farms: “don’t like it” because it is too hard and a long ways away]
[We aren’t ready for baseload – “need to reject coal first”]
[Too dense for manufacture]

BIPV – cost reductions through credit for glazing mtl [materials].

Q4. What are your thoughts on the storage/intermittency issue?

Mixed energy portfolio
Spreading the function to 6 hours E → W coast

[“Grid is storage” (early); PV + hydrogen (later)]

Off grid will require more storage solutions
Developing world will drive this demand
[PV will borrow from other solutions, transportation may provide some of these]

H_2 has to be the long-term, CO_2-free/pollution-free storage medium. I see PV fields also having direction photoelectrochemical-photoelectrolysis units also incorporated (not electrolyzers connected to photovoltaics).

[Up to 30%: use the grid as storage; Load management and/or storage to extend penetration levels]

Not essential for moderate penetration of PV.
Improved storage will leverage PV esp. for rural/off-grid and energy security.

Very important in 20 years [at ~10-30% penetration]

[Can’t be baseload]

If cost driven → PV stand alone
If security driven → PV + battery and dispersed systems

Q5. What are your thoughts on the relative advantages and disadvantages of the various deployment incentive instruments (RPS vs. feed-in tariffs vs. carbon portfolio standards, etc.)?

All will be needed initially to boost awareness and to provide current in a mixed-energy portfolio

[RPS is great, provided solar write-in.
Feed-in-tariff: good, provided it makes "business sense" and is "production oriented" (vs. straight rebate)
Carbon portfolio standard: disincentive for investing in future technologies?]

I prefer the carbon tax on all non-renewable carbon containing fuels based on the C intensity on the fuel (coal > methane). I realize that politically this is the most difficult.

Feed-in tariffs are best way as they reward the best system since it is based on what it produces.

[Feed-in tariffs: most effective in general, incentives for the "right behavior"
Tax-incentives are most effective in the U.S. (because of non-national standard for feed-in tariffs)
RPS and carbon portfolio are "OK", but carbon standards just let you "buy your way out of the problem" and not solve it.]

RPS has psychological benefits, customer wants to get paid back today not for 20 yrs. People afraid of unknowns causing system output decreases, like neighbors tree shading roof. What if your installer is out-of-business? Where do you go for redress?

Rebates (in $/W) don't reward production
Feed-in tariffs (cents/kWh) reward production and will ultimately be the best political choice

[Feed-in tariffs are good, but they have a political problem]

Feed-in tariffs are proving to be effective to accelerate market development
Any incentive needs to be "long-term", i.e. $\geq$ 10 yrs.

Q6. What do you expect in terms of balance of systems improvements and prices? What percentage of total system prices will BOS constitute in 2030? In 2050?

BOS improvements and prices should follow similar learning curves and will constitute 50-75% of price barring revolutionary improvements

[Good engineering will solve the BOS issues, < 50%]

Inverter cost ↓ 50%, efficiency ↑ to 99% [not yet optimized for this application]
2030: 20%
2050: 10% [to 15%]

40-70% (goal to make module cost low relative to BOS)

Typically BOS represents ~50%, will probably stay there.

[BOS "should be 30-40%" today (installation makes it higher) – will be 30-50% in both 2030 and 2050]

Inverter price should fall w/increase in market + volume.
Rail, wire, fuse all commodity good not expected to come down in price.

BOS will decrease by economies of scale and will be much less than $0.75/W
-2030: 50% ($0.30/W)
-2050: 40% ($0.20/W)
e.g. Look at history of cost for pots and pans, materials costs are presently small for BOS costs.
[Today: 80% is material cost for mature technology.]

[Ratio will stay the same: "it has to." If you don't do it in BOS, you will hit barriers. It will work, so it must happen]

Inverter eff[iciency] and reliability improvements → prices will stay at 50/50

Selected Comments

[On synergies and lowering costs: This survey is “partitioned by semiconductor,” but this is “only a third of the…total” cost of the module. Two-thirds of the device price will be in common components. Getting rid of a module frame or double-sided glass, for example, is a huge cost savings that can be enjoyed by all technologies.]

[One efficiency point gain (e.g. 15% to 16%) = $ 1 million/year in production cost savings (assuming production capacity of ~1 MW/year).]

CdTe efficiency improvements will stop at 15% without more R&D

[Deployment money keeps interest going in the short term. R&D is important in the long term for “extremely low numbers.”]

[Si has highest probability of achieving “reasonably low numbers.” Other techs could reach lower numbers, but probability is lower… at $1.20/Wp, there is “almost no incentive” to bring costs down. Thin-films are limited by lower efficiency (i.e. higher BOS) and lifetime and will need to be < $1/Wp.]

[By 2030, PV will be “a few percent” of electricity.]

[Rooftop → flat plate; with wholesale, “concentrators kick in.”]

[Intervals in detailed portion of the survey are “more like 90-95% confidence intervals” than absolute highs and lows.]

[More optimistic about the future than the status quo.]

[On “status quo” scenario: “At the moment, status quo is evolving”]

[Exitonic, esp. TiO_2, will be able to “bootstrap on aesthetics” and leverage marketing of this aspect]

[If there is to be a "new way" to make solar cells, you can't count on the current manufacturers to do it. Need to go to R&D.]

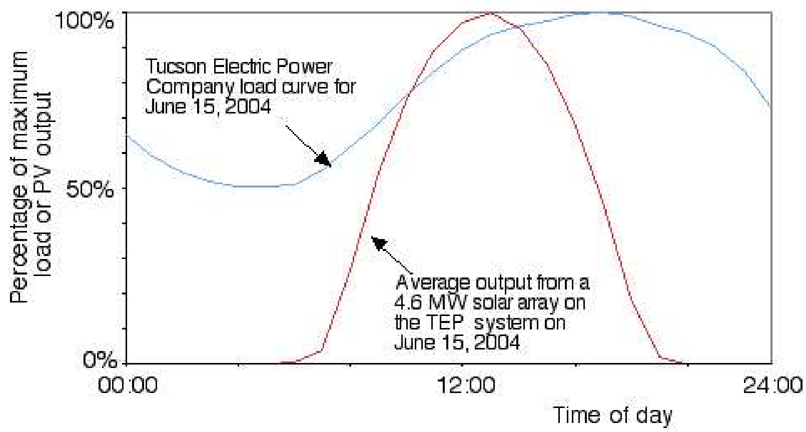
[Cost of glass (which is hard to replace) and other necessary components will limit how low things can go – will make $0.30/$W_p$ virtually impossible in 2030, difficult in 2050.]

[Would like to have seen an intermediate benchmark, e.g. $0.90 or $0.60/Wp]

["Self-organizing" (like plants and animals) "photovoltaics" are the key to ultra-low prices, e.g. spray-on algae that would produce electricity]

Discussion

Often utility load curves, and associated marginal prices for power, peak during periods when there is little or no sun, as illustrated in Figure S6.



Sources: (1) PV output data: Tom Hansen of TEP and (2) Load data: Ventyx Inc. Velocity Suite

FIGURE S6. Illustration of the mismatch between peak output for PV and peak load for a real utility system in Arizona in June 2004.