SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

HelioCon Roadmapping Workshop – Advanced Manufacturing Breakout Session Recap

Randy Brost, Sandia

November 10, 2021

THANKS

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Many thanks to:

- Participants!
- Heliocon leadership team.
- Organizers/Support:
    - Cindy Gerk
    - Linh Truong
    - Kailey Wulfert
    - Kelly MacGregor
    - Parthiv Kurup (co-lead and notes)

Process

Scope includes design, field installation.

Open discussion:

- What Gaps Do You See?
- What New Capabilities Do You Desire?
- What New Resources Do You Desire?
- What Have We Missed?

Laboratory ideas – Seek key heliostat-specific processes.

Prioritization.

Example: SESSION 1

What Gaps Do You See?

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Advance installation, foundation/pile installation.

Quality has a big impact on cost. Mass manufacturing tightly coupled with field construction. Thus quality control in installation is insufficient, driving up cost, and having a strong impact on final performance.

Need more cooperation with established high-volume industries (e.g, automotive). Could we use their facilties, experience, even for material supply?

Optical assessment tool used when heliostat is made (both factory and field). Well-established, respected by banks, traceable, verifiable to reduce risk. Cross-checking measurements in systematic database. Link to system model.

… established in industry already (e.g., deflectometry is accepted by banks). Outdoor trickier, has opportunities. Indoor slope error is covered. But calibration is a separate entity, multiple approaches.
…Established quick laser-based control system, 0.2 mm accuracy, checked slope error from factory; okay in assembly building, controlling canting and curvature. Second issue is tracking/calibration. Typically started when solar field is finished, connected to wiring. Proposed in Atacama, began calibration at beginning go of solar field construction, use image processing to compare against factory results.
…considering lasers for similar reason. But there is a problem not universally accepted. Therefore a bankable independent assessment would be of huge value.
…laser problem can't see mirrors directly. Need to use differencing technology.

Sum: In factory exists, outdoor needs improvement and earlier start beneficial.
…A key factor is whether facet is self-supportive. If not self-supportive, then canting can induce slope error and warping.

Risk reduction is a problem in multiple aspects. Suggest standardized processes to reduce risk reduction.

Potential Examples:

Factory metrology is inadequate.
Field metrology is inadequate.
Research tools are not available/supported.
Not enough vendors of CSP components and tools.
Mold/fixture cost ⇒ too few discrete focal lengths.
Precise mirror mounting point control is difficult.
Canting control is difficult.
Heliostat assembly transport is difficult in wind.
Supply chain is not robust for X.
Labor content/cost is too high.
Automation is too expensive/difficult to use.
Automation is not mobile.
Raw material cost is too high. (Especially material X.)
Raw material cost is too variable across locations.
Raw material cost is too volatile. (Especially material X.)
Field calibration is too slow/expensive.
Site infrastructure falls short, but shipping too expensive.
Wind loads are not well understood.
Washing force prevents material reduction.

What New Capabilities Do You Desire?

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Azimuth drive is more difficult than elevation drive. High stiffness together with low backlash and torque resistance requirements. Lack of solutions on the market implies self-develop drives.

Drives have been a lot of work, plus companies to self-assess drives to determine whether it meets technical requirements. Therefore would be really good if a drive meeting standards was available. Life, maintenance, backlash, static and dynamic loads, accuracy. Cost vs. quality trade-off.

Spasmodic market has been a problem.

RCB: Diversity of design dilemma?

Large size hit limit of electromechanical → large requires hydraulics. Small allows smaller design, but market solutions don't exist. PV solutions have high backlash. Small size lacks solutions.
…Suggest working with automotive industry. Learn lessons from them.

Facets: Two options: 1. Self-supportive (sandwich; e.g. glass-foam-glass or Al. Benefit CTE invariance. Otherwise glass-to-steel leads to slope variation with temperature. Doesn't lose optical slope when canting adjusted. 2. Not self-supporting. Lower mfg cost, but higher quality cost and assembly cost. Which option is best?
RCB: What would you like to see?
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…Desire creep prediction for sandwich facets.
…Creep analysis important for other types of facets as well.
Millions of m2 mirror made per year, but few for heliostats. Thus encourage high-volume glass supplier, and have another stage to add CSP features, have a fact product line. Requires large enough market. Therefore include glass suppliers.
…Professor Angel has good technology for precise mirror surface control. Suggest examining such technology for manufacturing precise resolution of contour mirrors.

Potential examples:

- Larger facets
- Better shape control
- Higher speed
- Faster-drying adhesives
- Metrology to measure X
- Metrology more compatible with factory environment
- Metrology outside
- Field assembly capability
- Multi-focal length molds

What New Resources Do You Desire?

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Our current practice is design for a wind speed, combination of torques in different directions. But we need a better, rich understanding of how wind loads specifically vary. Information is insufficient to allow us to optimize design. More complicated due to variation of h-to-h spacing within solar field. How does this affect loads?

…Standards often give turbulence intensity and speed profiles down to a certain height, but for small-to-medium heliostat, the data do not address the corresponding low heights. Data is not available.

…Wind data is not universally available world-wide. Much for some countries, little for other countries.

Time variation between average and gust not sufficient, both in magnitude and frequency. Can make operational decisions difficult. When to stow? Site-to-site relative pattern difference.

RCB: Would you consider grading heliostat strength due to position within field.

… Yes, we even vary drive type based on solar field positions. Need to coordinate with assembly of solar field.

…Design guidelines for choosing an effective solution of different data situations (lots-o-data, scant data…).

Heliocon has a plan to assess site-specific wind loads. Interest in assessing site wind loads?

…There is a trade-off with customizing vs standardizing design. Consider a span of designs.

RCB: need for process knowledge?

…Current sandwich mirrors 7.2 m^2; better than 0.8 mrad, multiple focal length, with same mold. Now limits are logistic; transport difficult.

Test lab facilities for drives. E.g., PV has range of standards, certified test labs. CSP could use the same.

Potential examples:

Design tools:

Mirror molding.

Rigorous tolerance analysis.

Test capabilities

…which ones?

Process knowledge:

e.g., how to mold very large mirrors.

e.g., mold filling stress, relaxation over time

e.g., glass annealing/spring-back models

Database of suppliers

Trade-off analysis reports

Trade-off analysis tools

What Have We Missed?

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Connections for power/control imply a drive for wireless solutions – need standards to support bankability. Different configurations have different requirements. Safety is significant. Independent testing and verification important. Also potentially low cost deployment.

…Re: Mfg. In addition to cost, what gain would a manufacturer enjoy if engaging in CSP. E.g., publicity and good will. Can we combine with other manufacturers, and they gain multiple benefits?

…Suggest high-quality alliances.

…Learn from other industry's processes – e.g., continuous improvement. However, volume limits can impede applying these lessons.

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→ Laboratory ideas – Seek key heliostat-specific processes.

Prioritization.

Prioritization

Suppose you are a program manager, and imagine that you have $4M ($4,000K) research funding available. How would you allocate the funds among these choices? See email and reply.

Scope includes design, field installation.

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→ Prioritization.

Example:

As we discussed, please reply and indicate how you would allocate 4,000 K$US in research dollars among the topic areas we discussed in the session. If desired, **highlight** sub-items of interest:

	K$	Gap 1.
	K$	Gap 2.
100	K$	Gap 3.
	K$	Gap 4.
	K$	New capability 1.
	K$	New capability 2.
	K$	New capability 3.
	K$	Resource 1.
	K$	Resource 2.
	K$	Resource 3.
	K$	Resource 4.
	K$	Resource 5.
	K$	Resource6.
	K$	Resource 7.
	K$	Missing 1.
	K$	Missing 2.
1000	K$	Facet fabrication – **optical accuracy**, durability, cycle time.
1,300	K$	Metrology – facet, **mold**, structure, field.
700	K$	Molds – **fabrication**, multiple focal lengths, ultra-large.
400	K$	Facet process – mold filling, **springback**, edge effects.
	K$	Multiple processes for different locales, volumes.
500	K$	Structure CAD tolerance analysis.
	K$	Right-the-first-time canting control.
	K$	Secondary optics.
	K$	Guidance for drive, control components.
	K$	Modeling – supply chain, production flow.
	K$	What else??

Target total = 4,000 K$

Bold underlines added by participant.

Numbers added by participant.

Prioritization Results (Preliminary)

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Votes	Total	Mean	Min	Max		
5	3,850	770	500	1,000		Easy field installation. Self-calibration.
6	3,300	550	400	750		Better wind data, understanding how to use it.
6	2,900	483	100	1,000		Metrology, across the board but especially in the field, certifiable and bankable.
5	2,850	570	50	1,000		Facet fabrication process understanding.
4	2,200	550	200	1,250		Increasing market certainty, US capacity.
3	1,900	633	400	1,000		Better ability to mass-customize components.
2	1,700	850	200	1,500		Low-cost, high quality drives for CSP, especially for small heliostats.
2	1,300	650	500	800		Design standardization, baseline design.
2	1,300	650	500	800		Test laboratories for drives, creep in mirror facets.
1	1,250	1,250	1,250	1,250		Political subsidies creating a reliable market.
2	1,200	600	200	1,000		High-quality, low-cost self-supporting facet.
2	900	450	100	800		Collaborate with other industries, e.g., high-volume, automotive, precision mirrors.
3	850	283	100	500		Educational materials to help bring new entrants up-to-speed.
1	600	600	600	600		Rules of thumb for fabrication, material, and component costs.
1	500	500	500	500		Quality control, including supply chain, statistical process control.
2	500	250	100	400		Wireless control and power. Standardization, safety and security issues.
2	450	225	50	400		Molds - fabrication, multiple focal lengths.
1	200	200	200	200		Data/knowledge framework for advanced heliostat research.
1	100	100	100	100		Better understanding of drive CSP issues regarding wear, calibration, and failure.
1	100	100	100	100		Better understanding of global heliostat manufacturing and markets, including China.
1	50	50	50	50		CAD tolerance analysis.

n = 7 responses (so far)

Comments:

- ??

Votes are still welcome!

Note: Not an accurate measure of preference. Instead, a quick summary to give initial feedback.

BACKUP SLIDES

SESSION 1

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Some Suggested Ideas

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Specific ideas:

Facet fabrication:
- Increase optical accuracy
- Increase durability
- Decrease cycle time
- Metrology – Facet
- Metrology – Mold
- Molds – fabrication, multiple focal lengths, ultra-large
- Process knowledge – mold filling, springback, edge effects
- Multiple processes for different locales, volumes

Output would include p
process development kn

Structure:
- CAD-integrated tolerance analysis
- Right-the-first-time canting control
- Metrology of structure, including without mirrors
- Field assembly techniques
- Field metrology

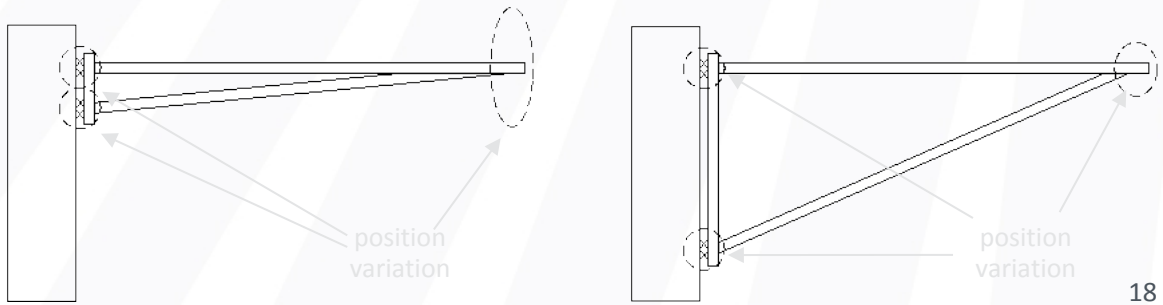
Output would include tolerance demonstration, knowledge of how to achieve it, supporting tools

Other:
- Fundamentally different design approach.
- Secondary optic manufacture.
- Adhesives.
- Factory flow/efficiency modeling.
- Supply chain modeling.

Comments:

What does industry vs. research do?
Industries have expertise in their specific areas.
Industry doesn't understand mechanisms, drives, gearing very well.
Why does calibration need to be repeated?
This is good area to reduce risk.

Example Geometric Tolerance Analysis



SESSION 2

What Gaps Do You See?

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Lack of standardization. Overdesign. Lack of clear understanding of wind loads, especially wind gusts. Design and size variation leaves open questions about how to optimize high-volume design and manufacture.

…Manufacturer involvement. It's difficult to motivate manufacturer and technology developers in the R&D part of the process, when there is not a project on deck (e.g, if there is not an imminent market).

…In the design and R&D phase, it can be hard to get realistic cost estimates.

…Re: Metrology. Optics development and metrology has to be developed interactively with customers. Do we need two types of metrology for factory and field, or the same? Need rapid, inexpensive, shop floor metrology technique. Field also is a need, which may be the same or different. *Characterization of requirements is key to developing a successful solution to these two problems. We need a table of requirements, varying wrt lab, shop, factory floor. Example: What is cycle time requirement? Is glass held vertically or horizontally? Are there other factory or context constraints? Vibration, temperature, dust, light,… need to characterize the environment. What is current work-in-process transport method, and can we make our metrology system integral with that, without a grasp/regrasp operation?*

Parthiv: Who is good to engage with?

…Broad industry is well-established. But it is productive to engage automotive suppliers, PV tracker suppliers, and other folks producing related products for another application at volume.

…engaging automotive and PV tracker industries will be difficult, due to low market size and differences in technical requirements

…Field metrology is expensive, difficult, and needs to be faster.

…A key solution approach would be intelligent heliostats that can calibrate themselves. Measurement of heliostats one by one will not be fast enough.

…Agree that field metrology is expensive. What's really expensive is if you find a systematic problem in the field. Therefore you need quality control in the upstream process. No bad parts arriving in the site. Input part/material stream verification. Supply chain control; bad supply chain control causes a cascading series.

…CSP plants have high production volumes. But when developing product, you don't have the tools or resources to develop automated or other high-volume processes. This makes it difficult to verify correct process operation, e.g. at speed, and also makes it difficult to determine whether you can achieve product quality/consistency goals.

Potential Examples:

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What New Capabilities Do You Desire?

Outside metrology capability. Accurate metrology outside. Also quick. Reliable…

Cristobal: Which type of metrology to do you perceive to be the main gap?

…Need is across the board. In situ, non-contact, rapid characterization of optical performance. Then work back up the line, because faulty components prevent assembly success, and in turn inaccurate tooling prevents component success. Metrology/quality control of finished heliostat, especially in final state in the field is needed.

…Note, sometimes the factory on site may be eliminated.

…Aiming control is a key metrology element, along with tracking accuracy.

…Outside metrology should be focused on aiming control and tracking. Once outside, we are late with canting and slope errors.

…But accuracy can change due to environmental factors. That said, you don't want to do field corrections.

RCB: Do fields have on-going refreshed information about changes in accuracy over time?

…Once installed, a heliostat could point in another direction, or it cold deform. Given a detection of a change, how do you differentiate cause? How correct?

…Access to state-of-the-art manufacturing systems and know-how. A big challenge during the R&D phase. Examples: Roll-forming, stamping, robotics, tubing, …

…Sophisticated manufacturing quality control know-how. Across the full supply chain stream. Barrier to entry for ~~smaller developers~~ folks who are early in the design process, who are not closely tied to larger volume existing process experts.

…Opportunity for rapid iteration. ***Tolerance of failure.***

…Funding contingent on success is reasonable, but it is productive to have a period where failure is allowed.

…A baseline design with associated costs could be helpful. It would allow people evaluate whether their cost reduction ideas are effective compared to the state of the art.

…Better ability to mass-customize components. Currently limited to one or two sizes. Example: Producing parts that appear similar in shape but different strength profiles. Different strength requirements at different parts of the field, and different optical requirements also.

…Corollary: Tooling accommodation to varying material thicknesses.

…Corollary: manufacturing flow/process control given such a product mix.

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What New Resources Do You Desire?

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Question: Does particle receiver imply north fields?

RCB: For now, Heliocon is open to surround and north fields.

…If we were to focus on north fields, then note that heliostats increase distance, and therefore optical error become more critical (for a given power level). Also affects heliostat size.

…National Labs able to provide to new manufacturers quick education. Data, information, reports to bring new entrants up-to-date. Example chapters: Include (a) economic motivation – what is the projected market, market size, economic drivers, etc. and (b) technical issues for CSP – e.g., technical environment and its consequent requirements for successful component designs and quality control. (One example: How to communicate with a manufacturer of car-door window mortors about the prospect of also building heliostat drive motors.)

…Need for training, and single-place location for related materials (e.g., a web portal).

…A resource like this would also help motivate educators, provide student resources, motivation, entrées to student research, etc.

…Example: A colleague working on control asks requirement details, but now there is nothing to hand to them.

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Test capabilities

…which ones?

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What Have We Missed?

Parthiv: Offer NREL/Sandia could share high-performance computing capability. Is this of interest?

…CSP requires IP. If we continue to import major portions of these systems, where does that leave us? For example, imagine a US company producing a new control system. But cannot produce in US at right price.

…Relates to increasing US manufacturing capacity and competitiveness with other countries. Regarding this topic, what has been missed by DOE/National Labs?

Some Suggested Ideas

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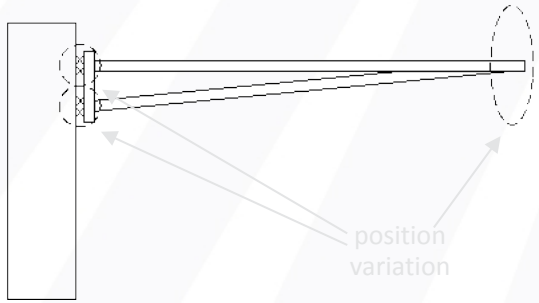
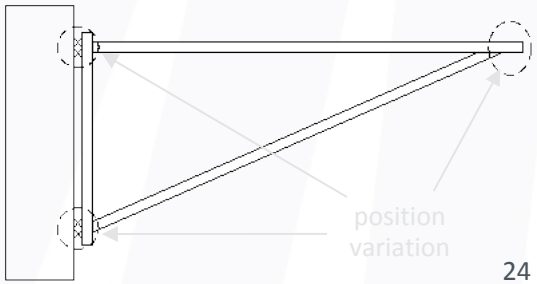
Comments:

Suggest 10-minute talk by experts on these topics, make available and post someplace easy to find.

…Labs can work with key players to help develops standards and processes.

…It would be great to work with developers to better understand handling procedures, and related documents.





SESSION 3

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…Standardization is needed. To achieve mass manufacturing, standard sizes will motivate development and construction of equipment (e.g, standard mirror facet size). PV presents examples, such as standard module size, enabling standard replication across the world. Current CSP diversity leads to difficulty in learning curve and other factors.

…Standardization has been mentioned for a long time. But has not appeared yet. Why?

…Lack of continuity of people. Industry players have viewed heliostats as a differentiator, which encourages different designs rather than standard. Too many engineering folks who don't think about mass manufacturing on a global scale. Site-specific optimization has inhibited progress on standardization.

…Level of automation is hard to determine, because market uncertainty causes uncertainty in market volume. Also site uncertainty adds to this, because where to build manufacturing capability is uncertainty.

…How to manufacture, especially in the field, has not been automated, increasing cost.

…Note that different cost of labor can lead to different process solutions in different locations.

…Facet shaping is a well-understood process.

…On the other hand, understanding wind loads and how to optimize heliostat design, and how it varies across the fields, is a gap in the information basis for designing optimal heliostats. This is especially true for large heliostats.

…Having a narrow range of sizes and form factors will encourage development across the spectrum of CSP components.

…One gap is a lack of consensus or clarity regarding optimization criteria. What exactly is the optimization goal? Consider Flextronics or Shinzen examples of contract manufacturers; can we get enough standards so that we can approach such manufacturers and incentivize them to engage?

…In other words, standardization could promote volume which would in turn promote investment.

…Heliostat costs have not dropped as quickly as other renewable technologies. Why so? Not due to lack of competent manufacturers; there is very good competency in manufacturing. What is the block? Is the gap in manufacturing capability or product?

…PV reached a standard module size, going back a decade, at the time when it was not cost competitive. It only reached low cost when mass manufacturing developed.

Potential Examples:

Factory metrology is inadequate.

Field metrology is inadequate.

Research tools are not available/supported.

Not enough vendors of CSP components and tools.

Mold/fixture cost ⇒ too few discrete focal lengths.

Precise mirror mounting point control is difficult.

Canting control is difficult.

Heliostat assembly transport is difficult in wind.

Supply chain is not robust for X.

Labor content/cost is too high.

Automation is too expensive/difficult to use.

Automation is not mobile.

Raw material cost is too high. (Especially material X.)

Raw material cost is too variable across locations.

Raw material cost is too volatile. (Especially material X.)

Field calibration is too slow/expensive.

Site infrastructure falls short, but shipping too expensive.

Wind loads are not well understood.

Washing force prevents material reduction.

What New Capabilities Do You Desire?

Easy field deployment. Self-installation, self-calibration. Rough initial placement and then self calibration. If feasible would have a rough position would suffice.

…In contrast, PV installation is simple and can be done by standard electricians. But CSP heliostat installation is more difficult and complex.

…Making heliostats easy to install and successfully calibrate would help. Mistake-proof, make robust and self-correcting. This would reduce cost.

…A PV example: Stacks of concertina pallets, easily deployed and placed. Suddenly performance optimization is less important compared to superbly low-cost, simple installation.

…Design is implicated by this. For example, no canting might be a design choice.

…Implies that preferred design would be to achieve this early, and then standardize on that.

…A base design would be helpful, because component-wise improvement, automation candidates, source countries can all be concretely evaluated. Thus DOE could down-select to a heliostat, just like DOE down-selected to the particle receiver.

Potential examples:

Larger facets

Better shape control

Higher speed

Faster-drying adhesives

Metrology to measure X

Metrology more compatible with factory environment

Metrology outside

Field assembly capability

Multi-focal length molds

What New Resources Do You Desire?

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…Should there be a framework for advanced manufacturing research. Includes metrology, physics model, computation. For example, an AI framework is too much of a black box. For example, if we had a real data stream of the information captured on a solar field, properly curated, would enable attack with various computational approaches. This would require a computational resource (a "brain"), a strong metrology system to capture the data, preferably in situ, and finally a database of collected data. This would enable computational researchers to study various diagnostic and optimization approaches. And not just computational researchers --- anyone who is investigating, using whatever technique they prefer.

…Heliogen wants to measure *everything.* Variation over time, adhesives, etc. This is an example motivator of collecting and curating data. This would require overcoming the barrier of companies sharing internal data.

…Desire to capture institutional knowledge and experience. Make large data available for analysis.

…In order to interest competent manufacturers, we need a pipeline of projects in the queue to provide financial incentive for their engagement. Thus there is a need for something that will give market credibility. PV has accomplished this, which began with substantial manufacturing investment subsidy in China. Could be difficult for Heliocon.

...Knowledge interchange is valuable. Once a year heliostat design report.

…Political support by subsidizing investment (e.g., Germany) could lead to market growth and then price reduction. PV is now the lowest cost per kWh source available (intermittent). Thus an analogous incentive program is needed, support it reliably until cost decreases.

…RCB: Modularity achieved by focusing on industrial process heat?

…Maybe, but that field is really diverse, increasing difficulty. It's hard without political incentive.

…PV analogy is imperfect, because small-scale CSP applications are not as readily available. A pipeline of larger projects would be most beneficial, but historically has been very stop-start.

Potential examples:

Design tools:

Mirror molding.

Rigorous tolerance analysis.

Test capabilities

…which ones?

Process knowledge:

e.g., how to mold very large mirrors.

e.g., mold filling stress, relaxation over time

e.g., glass annealing/spring-back models

Database of suppliers

Trade-off analysis reports

Trade-off analysis tools

What Have We Missed?

In past experience, CSP thermal was expensive to market and sell, compared to profit margin. Thus it would be helpful to have a context that encourages that development.

RCB: How much would volume help?

…Yes, because continuity of production would yield consistent infrastructure capability, and also a reliable revenue stream, and easier attraction of investment, enabling simultaneous optimization of both cost and revenue.

…A better understanding of heliostat technology, manufacturing, and markets across the globe would be helpful. Including for China, for example, which is where there is a lot of current activity, yet not participants in the workshop.

Some Suggested Ideas

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Specific ideas:

Facet fabrication:
- Increase optical accuracy
- Increase durability
- Decrease cycle time
- Metrology – Facet
- Metrology – Mold
- Molds – fabrication, multiple focal lengths, ultra-large
- Process knowledge – design rules, mold filling, springback, edge effects
- Multiple processes for different locales, volumes

Output would inc
process developr

Structure:
- CAD-integrated tolerance analysis
- Right-the-first-time canting control
- Metrology of structure, including without mirrors
- Field assembly techniques
- Field metrology

Output would include tolerance demonstration, knowledge of how to achieve it, supporting tools

Other:
- Fundamentally different design approach.
- Secondary optic manufacture.
- Adhesives.
- Factory flow/efficiency modeling.
- Supply chain modeling.

Comments:
Interesting but long list.
…Triage in terms of low/med/high risk, also effort level. Allow for discovery process. Support by entertaining support for low-TRL research as part of the portfolio. National laboratories might help bridge fundamental to applied gap.

Example Geometric Tolerance Analysis