Solar Beyond Grid Parity Workshop

TECHNOLOGY OPPORTUNITIES BREAKOUTS

Thursday, April 12

Solar Beyond Grid Parity

TECHNOLOGY OPPORTUNITIES BREAKOUT

Breakout 1 : Complete Spectrum Usage

What is the state-of-the-art in directing photons to where they are best utilized in solar systems?

- **What low-cost optical elements or techniques can increase the efficiency of solar systems by directing the photons where needed?**
  - **Dispersive elements/spectral splitting:**
    - Holographic – inexpensive manufacturing and very dispersive, but highly wavelength dependent; encapsulation durability needs improvement
    - Bragg mirrors (1-D photonic periodic structures)
    - Dichroic mirrors (multi-layer) – available but may be too expensive
  - **Focusing:**
    - Polymer lens – easy to manufacture and offers Fresnel efficiency improvements, but durability remains a challenge
    - Mirrors – High concentration increases tracking cost
    - Luminescent solar concentrators: currently limited by their low efficiency
  - **Coatings / Materials:**
    - Super hydrophobic coatings (cleaning of optics)
    - UV resistant polymers: not there yet for higher concentration solar
    - Texturing
    - Anti-reflective coatings – low-cost, but porosity and small area are limitations

What is the state-of-the-art in directing photons to where they are best utilized in solar systems?

- **How do spectrum-splitting component choices depend upon the concentration ratio (and angular spread of incoming light) it must split?**
  - The two are intimately linked – this represents a trade off space / optimization space
  - The optimal location to place spectrum-splitting components is an area of active debate
  - The cost effectiveness of spectrum-splitting remains an open question

What new advances [e.g., photonics, nanoscience or fibers] could provide breakthrough improvement?

- **What promising new methods could dramatically improve the efficiency of (or reduce the costs of) solar systems by directing the photons where needed, compared to the methods known today?**

  - Advanced polymer engineering – should provide more choices to the system designer as well as wider transmission bands and lower water transmission in certain applications
  - Dispersion optics
  - Thin slab concentrators - should reduce the volume of the optics, but manufacturability is an issue
  - Injection molding large area optics with high uniformity
  - The use of optical fibers – offers improved uniformity and manufacturability, but dB losses are significant over a wide spectrum and coupling light into the fiber remains challenging
  - Capturing both direct and diffuse light
  - Better ways to split, trap and upconvert incident light
  - Engineering interfaces to capture light
  - Low-cost angular agnostic trapping filters

What new advances [e.g., photonics, nanoscience or fibers] could provide breakthrough improvement?

- **What possible materials science or technological breakthroughs are needed to enable higher performance optics of this type?**
  - Lower cost tracking that maintains accuracy
  - Highly engineered materials, chemically engineered, designer dielectrics
  - Understanding material robustness and failure mechanisms over time in typical environmental conditions
  - Improvements in mirror uniformity
  - Scaling down elements and overcoming the PV cell / package integration issues + thermal benefit

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Breakout 2 : High Efficiency & High Temperature Photovoltaics

What are the technical opportunities for high-efficiency solid-state sunlight-to-electricity devices at high concentration and temperature?

- **What are the main barriers to bringing solar devices close to the Shockley-Queisser thermodynamic limit when operated under concentration at ~ 200 to 400°C or even higher?**
  - Metallization
  - Thermal expansion mismatches – die attachment material
  - Lifetime – dopant migration (Zn in particular)
  - Oxidation of III-V materials
  - Thermal cycling

- **How can these barriers be overcome?**
  - Better encapsulants/packaging materials are needed
    - Packaging expertise from high T power electronics community needs to be leveraged – this community has worked on these issues so the risk is likely low

- **Can multijunction solar cells, thermoelectrics, photothermionics or other types of devices improve the high T performance, compared to single junction PV?**

How efficient are today’s single junction cells under these conditions?

- **How close to their ideal high T performance can 1.6 – 2 eV bandgap solar cells be when used at ~200 to 400°C or even higher?**
- **What are the most promising semiconductor materials known today at each bandgap? What are their drawbacks at each bandgap?**
  - **GaAs** (start from the best we have now, specific benefit: high mobility)
  - **InGaP**, 1.8 eV (benefit: high ERE)
  - GaP, 2.26 eV
  - InGaN (has exhibited good performance above 2.5 eV)
  - Si should not immediately be dismissed entirely due to the large processing know-how we currently have
- **Which bandgaps would require materials or device configurations beyond today’s best and what might they be?**
  - We should start from today’s best materials and modify as needed
    - Materials are worth considering if they have high ERE and/or if they make good LEDs
    - Don’t focus only on the material bandgap
  - New high bandgap materials (e.g. ZnGeN alloys) might have long term promise but are currently at a very early stage of development

What innovations are needed to make solar cells survive long term operation at high temperature?

- **What unique problems (e.g. durability, contacting, adhesion) would operating at 200-400°C or higher, at high concentration, bring for single and multijunction cells?**
  - Adhesion of solar cell components will be a challenge
  - Risk of thermal runaway increases at higher temperatures
  - Semiconductors are usually more robust than the encapsulant materials
  - Die attachment materials will have durability challenges
  - Validation of reliability will be difficult - new accelerated life cycle testing procedures will be needed
  - Localized heating could become a problem
  - Heat gradients from the front to the back of the cells will pose thermal management challenges

- **What are the promising solutions to these challenges?**
  - Considering different cells sizes could offer some options to deal with the challenges

- **Would the use of peeled cells or low-radiative emission cells bring special problems for high T durability?**

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Breakout 3 : System Engineering

What possible technological breakthroughs would be most valuable for the integration of PV with thermal collection systems?

- **What are the costs and benefits of integrating PV into a solar thermal collection system? How does this depend upon the type of concentrating system (tower, dish, parabolic trough, lens) being used?**
  - Optimize the efficiency vs T for PV and CSP: Figure of merit may be ($\eta \cdot T$)
  - Optimal geometric scenarios depending on concentration:
    - Utility industry 1-D - flat panel
    - If 20 suns – PV should run along the line of parabolic trough
    - If 500 suns – PV should run along the line of power tower
  - Running fluids inside tubes in parabolic troughs is easier than in power tower systems (the form factor is more amenable)
  - Open question: What is the value of dispatchability – (1.5 ¢/kWhr?) – should energy be dispatchable seasonally or all year long (e.g. high energy density fuels)
  - Open question: Where is the right place to place concentration – before or after PV?

- **What possible breakthroughs in receivers, thermal fluids or heat engines are needed to enable new designs for solar plants that collect heat and electricity?**
  - Thermally decoupling heat harvesting may lead to higher overall efficiencies
  - A means to deal with the temperature gradient across the PV material is needed, target gradient of only 2-3 °C from front to back side
  - Possible design idea: PV operating at 300-400°C. Fluid heated up to 300-400°C- and then boosted further to 600°C by concentrators.
  - Need inexpensive phase change materials (PCMs) that are stable for a range of temperatures (300°C – 1000°C). If PCM is a metal, it could destroy the back of the PV cell.

What technology breakthroughs could enable better utilization of the solar spectrum?

- **What innovations can enable fuller utilization of solar energy while lowering costs compared to today's technologies?**
  - It may be possible to convert UV photons to electricity, but making an AR coating will be difficult
  - Use PV photons for PV and 'route' the rest to thermal – the solar cell can be the splitter
  - Photon recycling through change of materials properties, but lifetime may be an issue
  - Run PV as hot as possible and run a high temperature engine for higher efficiencies
  - Run PV at low T at 30%, and use a low temperature organic Rankine at 10-11% - this will likely get over 40% efficiency
  - Would be beneficial to integrate PV into existing CSP plants – even a 5% gain would be beneficial
  - It is easier to design reflectors at narrow bands

- **What problems does optical splitting present to today's CSP thermal or optical system designs?**
  - PV is spectral dependent while thermal is not spectrum dependent
  - Interference filters do not currently perform well
  - High temperatures are not expected to pose a problem for spectrum-splitting optics
  - Open Question: are there issues with electronics and wiring?

- **Where in each type of concentrator system (tower, dish, trough, lens) would it be best to integrate optical splitting elements?**
  - UV and visible light could be removed before concentrators for CSP systems which may lead to cost savings

Where might you put the PV into a thermal collection system and how would it affect CSP performance?

- **If PV were free, where would you put it into a CSP system today?**
  - Running PV at high temperature may make sense in certain circumstances, but co-optimization of PV/CSP will need to take place - efficiency may go down but overall power production may increase
  - Dispatchability from PV would be a value-add to CSP
  - Open Question: Is there a PV technology that can survive high temperatures (>200 °C)? PV cells able to function at >300 °C may not be necessary.

- **What are the pros and cons of designing a solar thermal system that collects heat at more than one temperature? Would tower, trough, dish or lens likely be best for this?**

- **What receiver temperatures might be particularly beneficial for high-efficiency and low cost?**
  - Going to 400°C just for heat does not make sense without concentration

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Breakout 4 : Dispatchability/Portability

What problems need technical breakthroughs to enable high efficiency and low cost production of energy dense fuels for: i) dispatchable electricity OR ii) transportation?

- **Is there leverage in using heat and electricity together?**
  - Yes, heat is less expensive than electricity
  - Full use of the solar spectrum improves the cost effectiveness of expensive heliostats
  - A systems level analysis is needed for each technology being considered (including cost, efficiency, value in pushing to more complex systems)
  - Heat can be produced with higher efficiency than electricity
    - Efficiencies: solar to heat→ 75% > solar to electricity→ 20%-45%
  - NIR can be used for heat needed for reaction and direct visible light to PV
    - 50% light to chemical conversion efficiency might be possible
  - Water electrolysis/fuel cell is a possible design but different reactions that do not split water with lower overpotentials may be alternatives (preferably liquid systems that do not produce oxygen):
    - HBr, HI, alkali-chlorine system
    - Metallic fuels, e.g., Mg, Zn
    - Sodium borohydride
    - Hydrogenation of toluene to methylcyclohexane

What problems need technical breakthroughs to enable high efficiency and low cost production of energy dense fuels for: i) dispatchable electricity OR ii) transportation?

- *High temperature electrolysis*
  - TΔS can be input as external heat, not electricity
  - No commercial electrolysis in intermediate temperature range (300-700°C) currently available, but there have been recent advances in this area
    - Unclear if there is an advantage to working in this temperature range
    - There is a tradeoff between using less durable SOFC materials at high temperature vs more durable low temperature electrolysis materials

- *Do you need to directly make a liquid fuel (i.e. what is wrong with H_2)?*
  - Water or water/CO_2 can be split into hydrogen or syngas to direct to Fisher-Tropsch plant
    - Where is the source of CO2 feedstock? Co-location with coal/NG plant or use of biomass is possible
    - Use H_2 for Haber-Bosch

- *Other Possible Systems*
  - Hybrid thermochemical
  - New material cycles using high temperature heat and low temperature electrolysis
  - Moving beyond thermochemical hydrogen, low temperature photoelectrochemical, biological systems

What problems need technical breakthroughs to enable high efficiency and low cost production of energy dense fuels for: i) dispatchable electricity OR ii) transportation?

- **Is it possible that photons could be used non-thermally in chemical reactions (i.e. not merely for heat) to improve storage or energy dense fuel production technologies? What are likely areas for such breakthroughs?**
  - Yes, photochemical reactions (direct or indirect)
  - Higher energy photons are not efficiently used in PV
  - Photoelectrochemical and chromophore-based systems (photoinduced electron transfer) are possible for indirect conversion, but cyclability will be a challenge
  - Photolytic reactions could be used for direct conversion, but the efficiencies are likely low and it is difficult to find reaction that use lower energy photons without irreversibly degrading the system

What breakthroughs are needed to make thermal/mechanical co-storage of heat and electricity useful?

- **Do we have the technologies and materials we need today?**
  - Yes, mechanical systems can focus on how can you combine components to get new, more desirable systems
  - This depends on temperature needed (200°C would be simple, 1200° C would be difficult)

- **Might combinations of chemical and mechanical approaches improve storage or dense fuel production?**
  - Possibly, but you need to keep in mind competing technologies
  - Adsorption technologies with high reversibility can already do this using zeolite materials to adsorb air

Is developing dispatchable electricity or energy dense portable fuels for transportation more valuable?

- **Which is more likely to change the amount of solar energy humans can utilize: making dispatchable electricity or making energy dense transportation fuel from solar energy?**
  - There is higher value in making energy dense fuels and a large market, but this is a more difficult problem

- **How would you quantify the value of each?**
  - 3.5x the entire current annual US electricity demand (4.1 million GW-hr/year) would have to be dedicated toward synfuel production to completely replace all of our annual liquid fuel demand (6.26 million kbbl)