CHANGING WHAT'S POSSIBLE

Beyond Grid Parity: Spectrum-Efficient Solar Energy for Dispatchable Electricity or Dense Fuels

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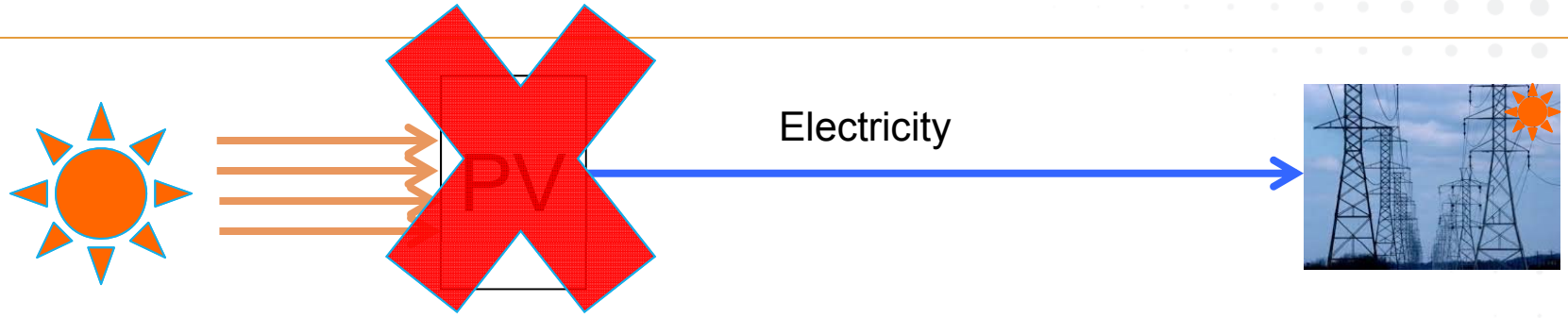
ARPA -E Program Director

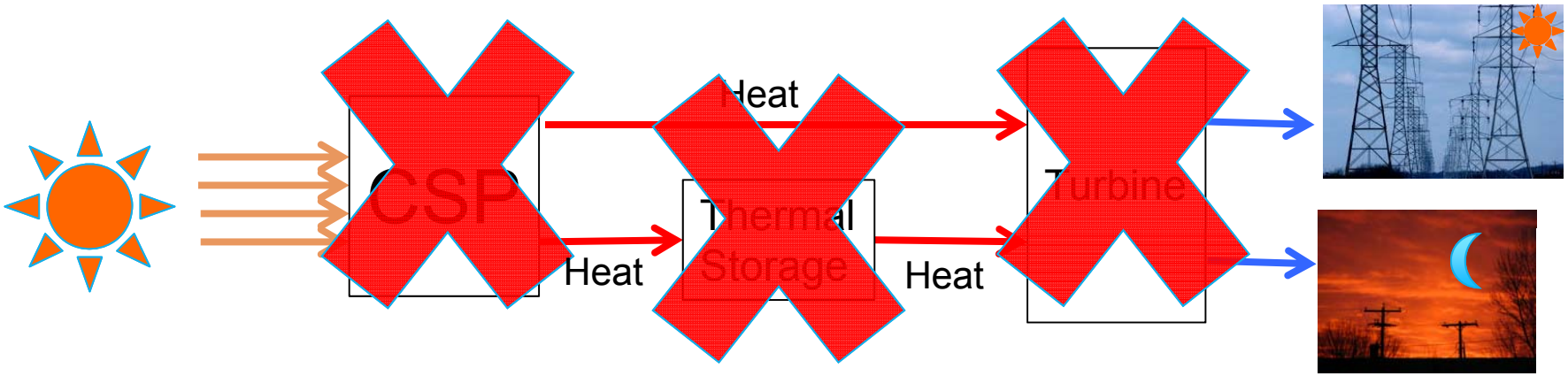
April 11, 2013

Thanks to Will Regan, Liz Santori, Brian Borak, Kacy Gerst & Joel Fetter

ARPA-E Program Directors: Jonathan Burbaum, Tim Heidel, Ping Liu

Today's Grid-tied Solar

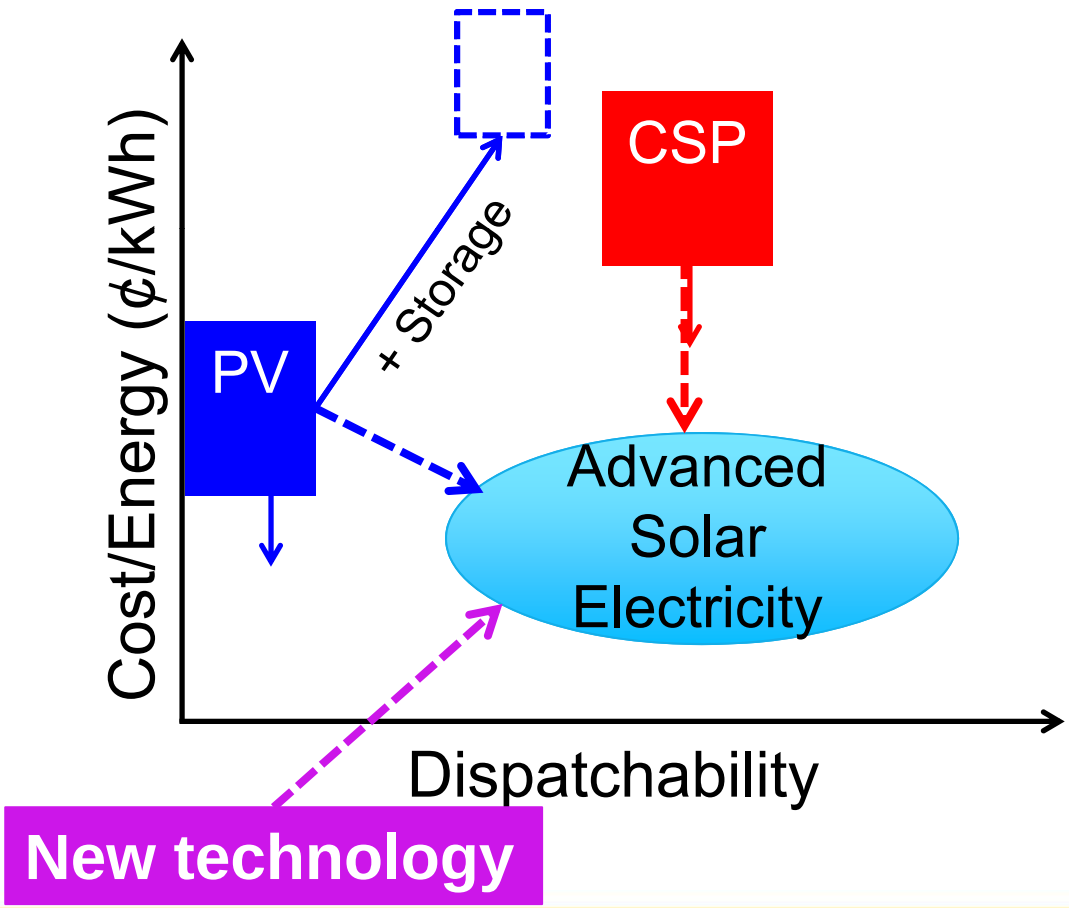




- Not incremental improvement to PV or CSP
  - Build on today's R&D in PV and CSP

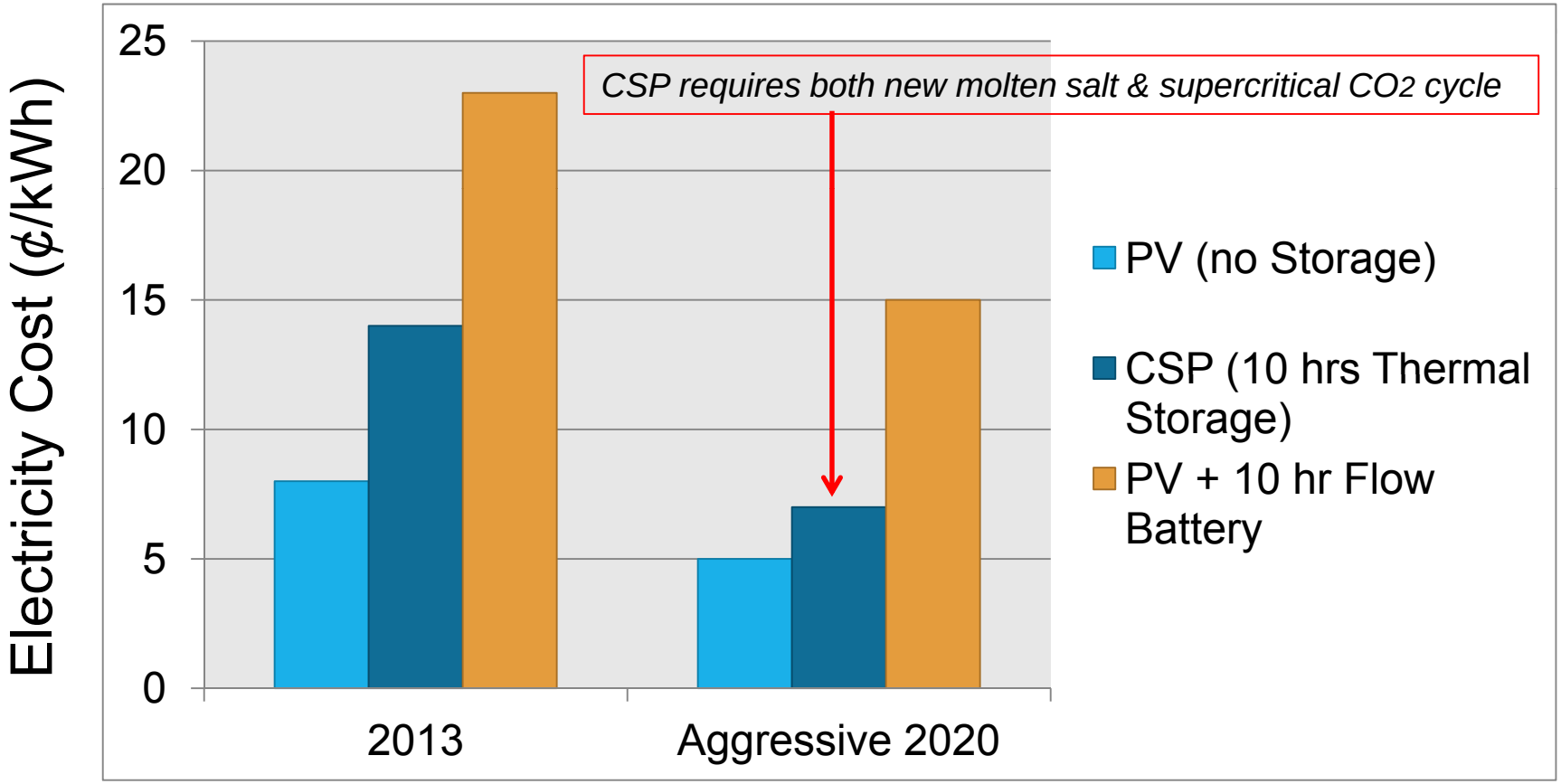
Workshop Challenge: Solar Beyond Photovoltaic (PV) and Concentrating Solar Power (CSP)

- Goal: Maximize solar penetration to reduce CO_2 emissions
  - Maximize economic value of solar



Levelized cost of solar electricity with storage

- 2020 costs estimated from aggressive Sunshot & ARPA-E Program goals with Investment Tax Credit



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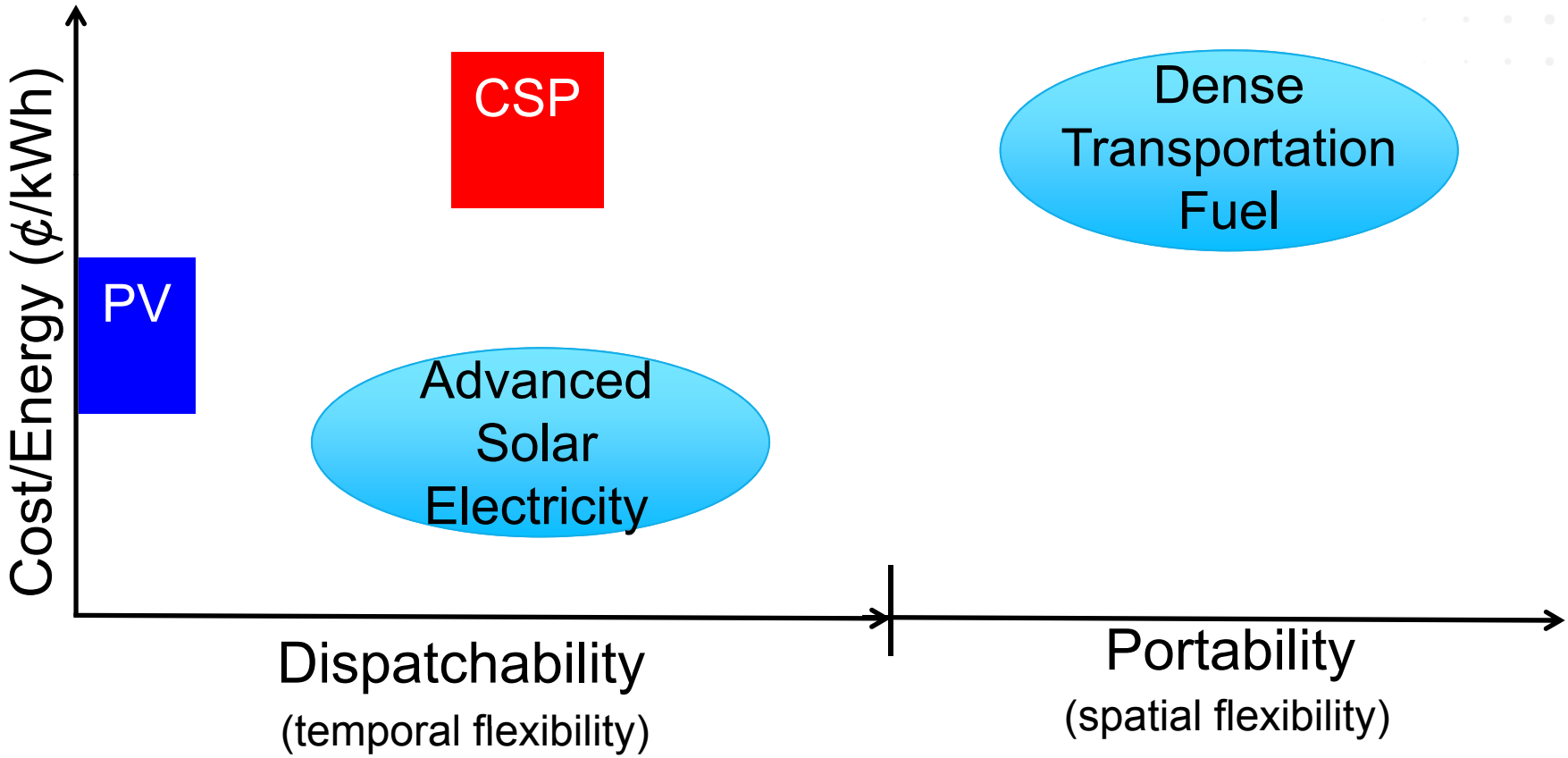
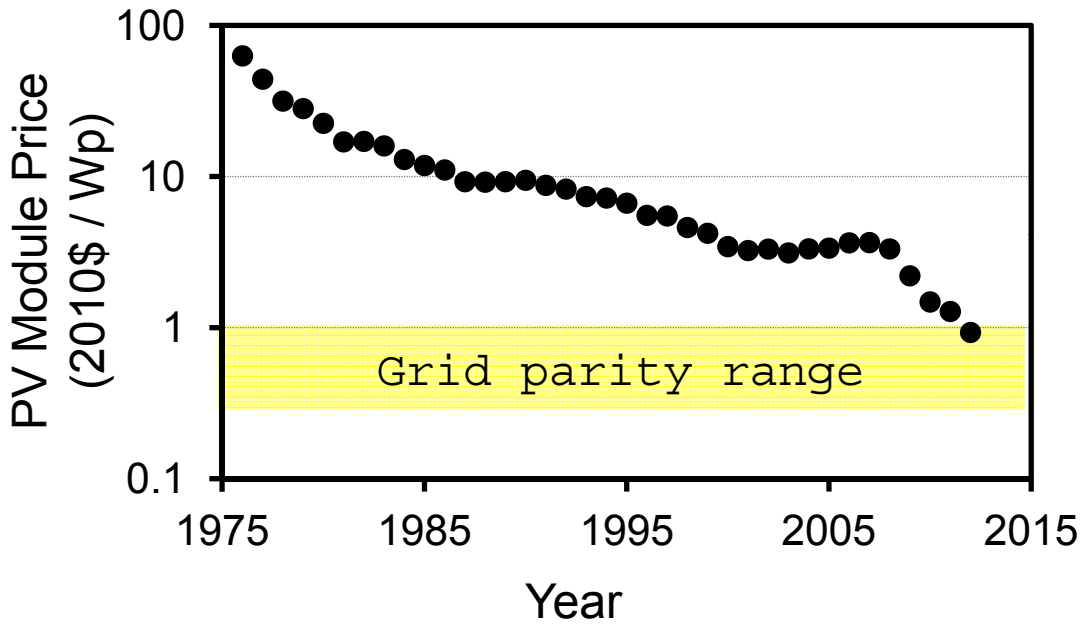


Photovoltaics (PV): Good news and bad

- PV electricity now below grid parity in sunny places

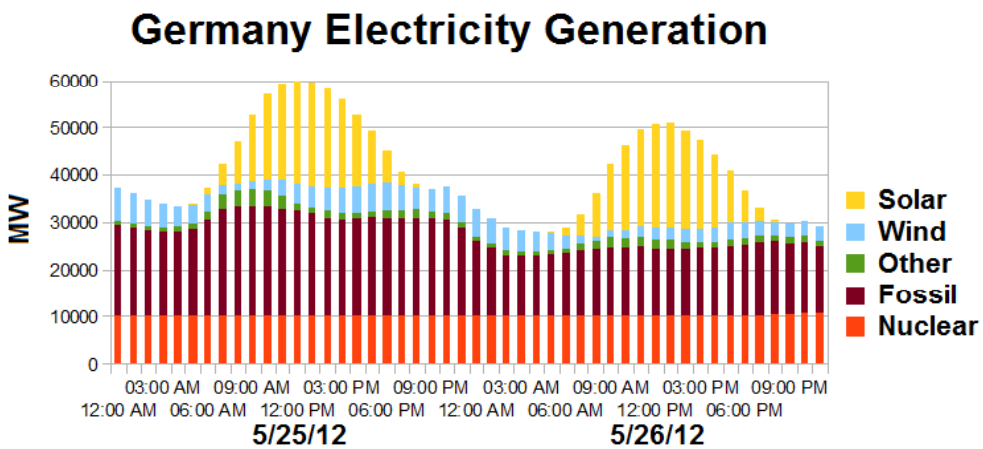


- Problem: PV electricity soon in oversupply at sunny times

Data Source: Navigant Consulting

Problematic future of "pure" PV is already seen in Germany

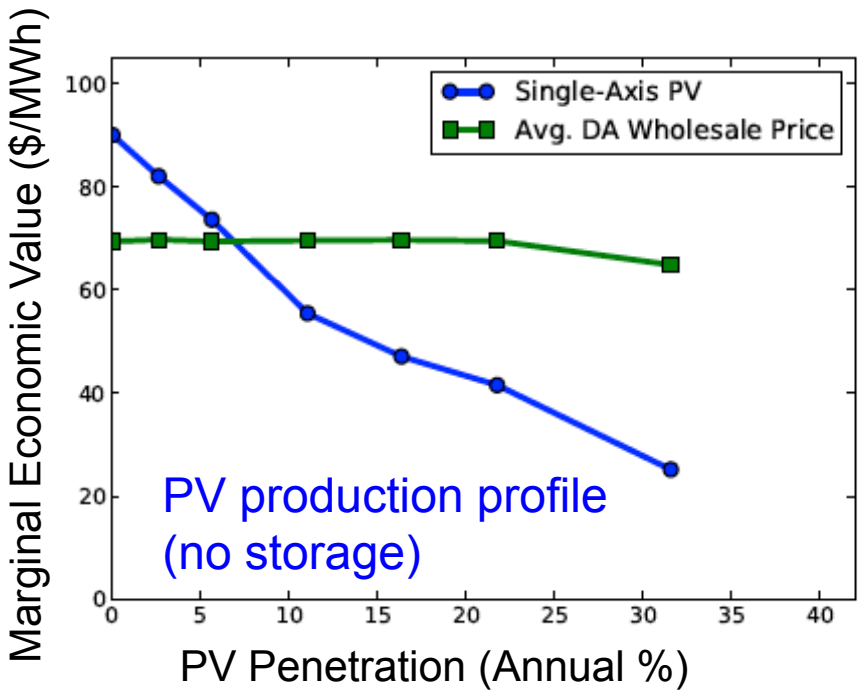
- Feed-in-tariff guarantees high price to PV generators
- High PV penetration
  - 5-10% of electric energy
  - ~50% of power at sunny noon

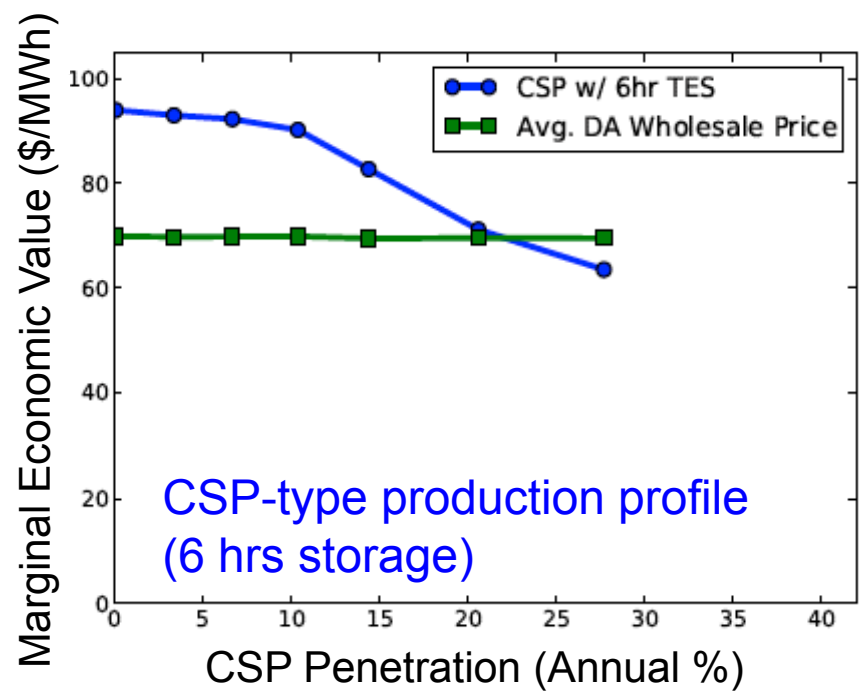


- Spot market for electricity changed dramatically by this PV
  - Old daytime price was > 6 €¢/kWh
  - Sunny day price now ~3.5 €¢/kWh
  - Germany: More solar PV looks like poor renewables policy
  - Free market: Sharply reduced PV investment
- Dispatchable solar needed

Economic value of PV falls at high penetration

- Varied the % penetration of solar in California 2030 simulation
- CSP-type solar with 6-hour storage holds its value better
  - PV "Capacity value" falls at >10% penetration
  - PV "Electricity value" falls at >20% penetration





A. Mills & R. Wiser, LBNL, June 2012

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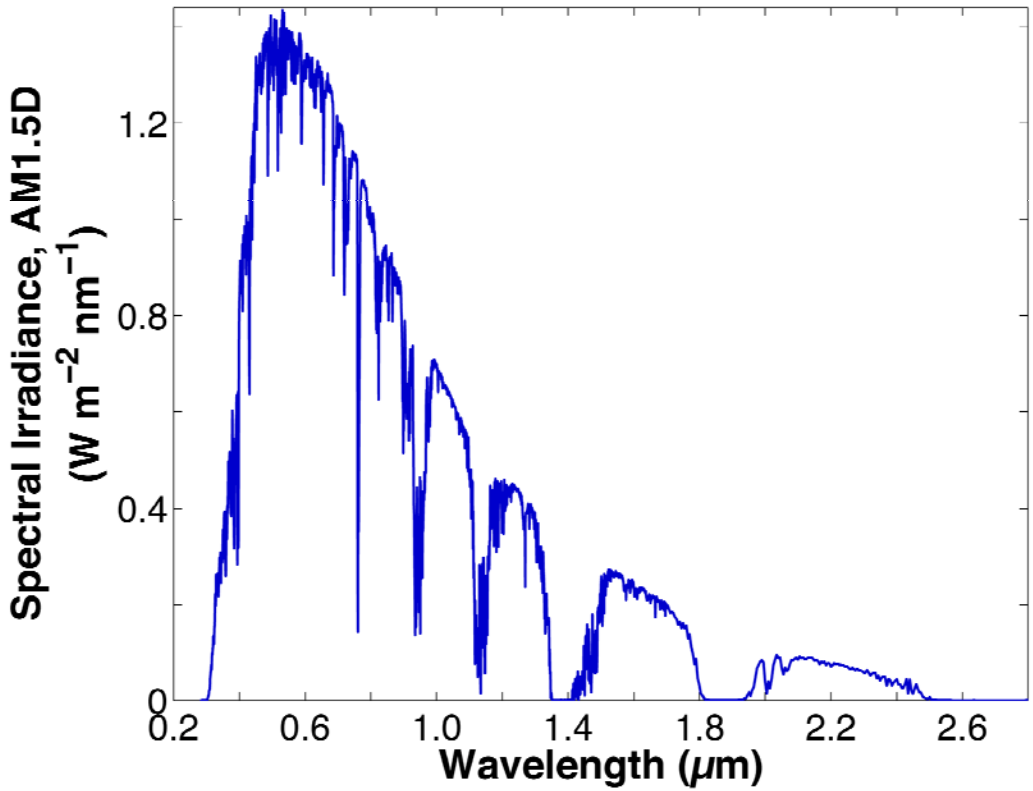
CHANGING WHAT'S POSSIBLE

Overcoming variability of solar

- Complementary renewable resources
- Interconnection of geographically dispersed sites
  - Improved grid
- "Smart" demand-side management
- Natural gas turbine spinning reserves
- Grid-scale storage remote from generation

- **Storage integrated with efficient solar system**
  - **Innovative, disruptive, technologies needed**
  - **The main subject of this Workshop**

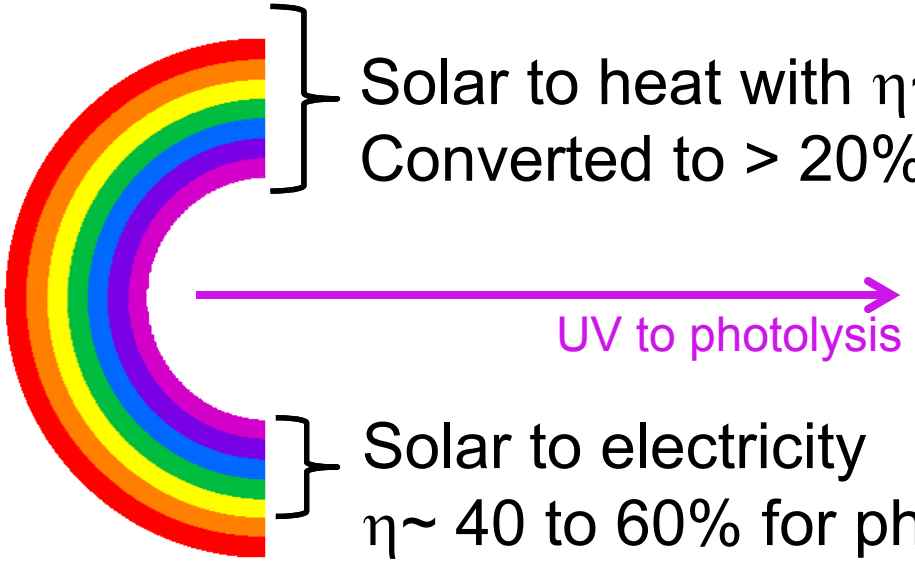
Solar feedstock for new systems solutions



- Solar photons
  - Photo-electrons & photo-holes
  - Solar-thermal heat
  - Photochemical reactions
  - ???

Optimized solar spectrum tools

- Use complete solar spectrum at high energy efficiency (η)



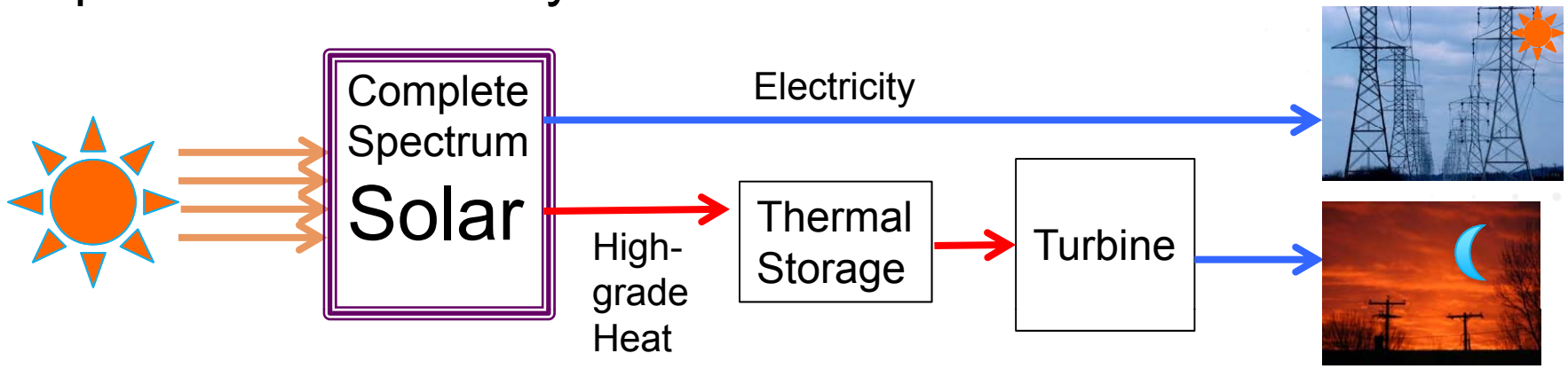
Solar to heat with η~60 to 80%
Converted to > 20% electricity

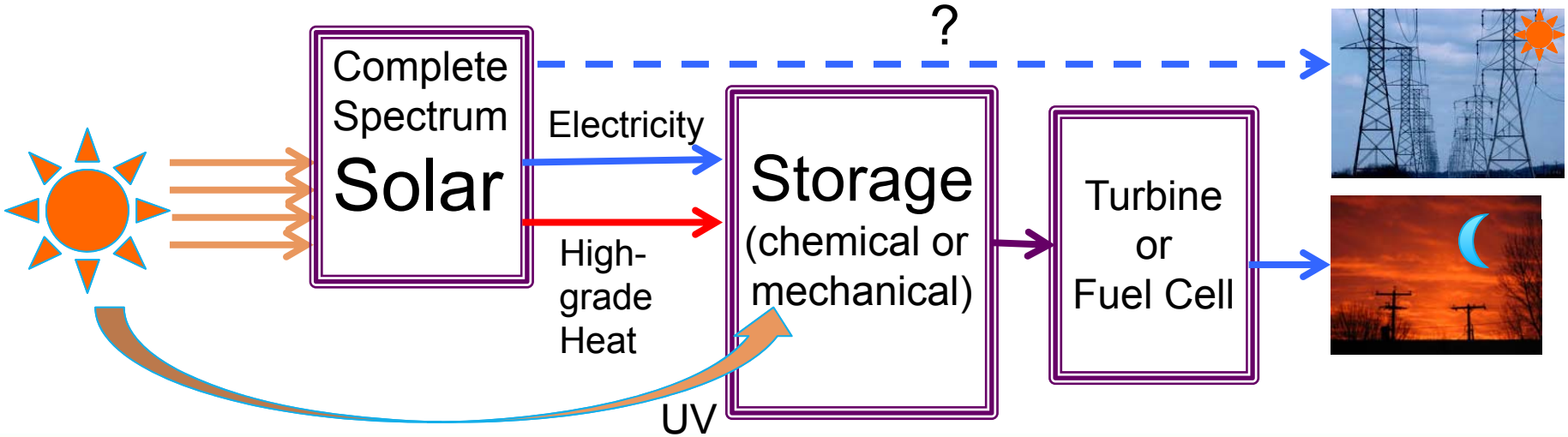
Solar to electricity
η~ 40 to 60% for photons just > PV band edge
(1 – 2 eV bandgaps work best)

- Optimize Heat:Electricity Ratio for efficiency (& storage)

Example ARPA-E Workshop Interest Areas

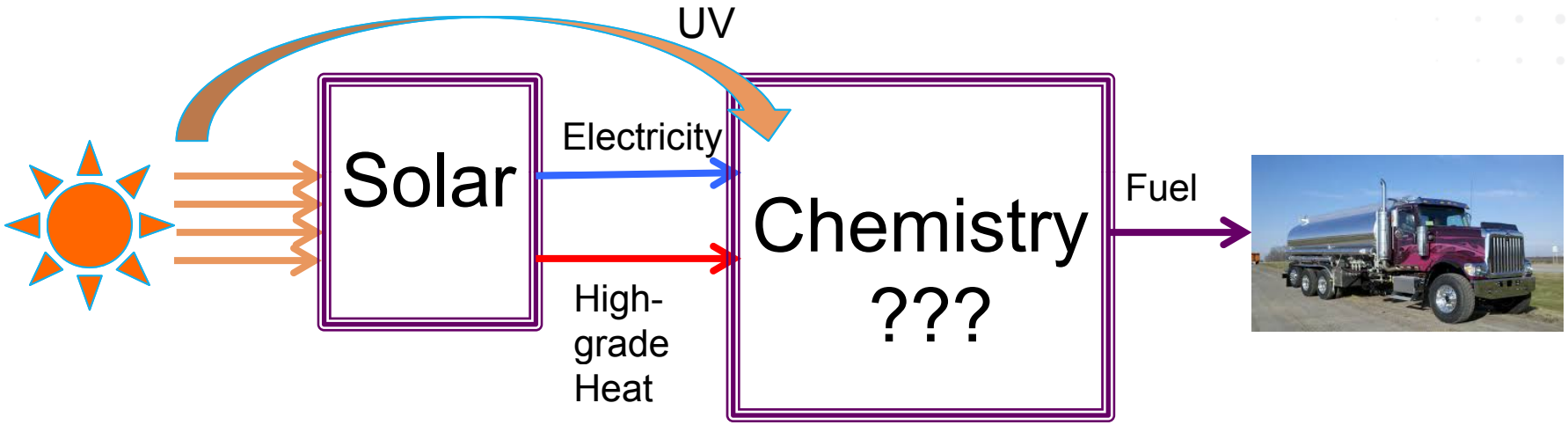
- Dispatchable electricity





Example ARPA-E Workshop Interest Areas

- Portability (dense transportation fuel ≠ H_2)



Solar Techno-economics 101

- Low 1 kW/m^2 solar flux but fuel is free
  - Large-area mirror or lens or solar cell array is costly
  - Cost of energy collection ~ 1/η
- Allowable capital cost from PV today
  - Module area cost ~\$150/m^2 at η~ 20% supports 8¢/kWh today
- Stored solar energy (at a cost) provided by CSP
  - CSP η~15-20% today and will be better as operating T increases
  - Relatively high complexity increases system cost
  - > 95% round-trip thermal storage for dispatchability
- Future inexpensive solar electricity
  - System efficiency much higher to reduce collection cost
  - Energy collection cost per unit area lower
  - Storage as good as CSP today (or production of valuable fuels)
- Future solar fuels must beat PV + electrolysis (η ~15%)

The pros & cons of showing specific design examples

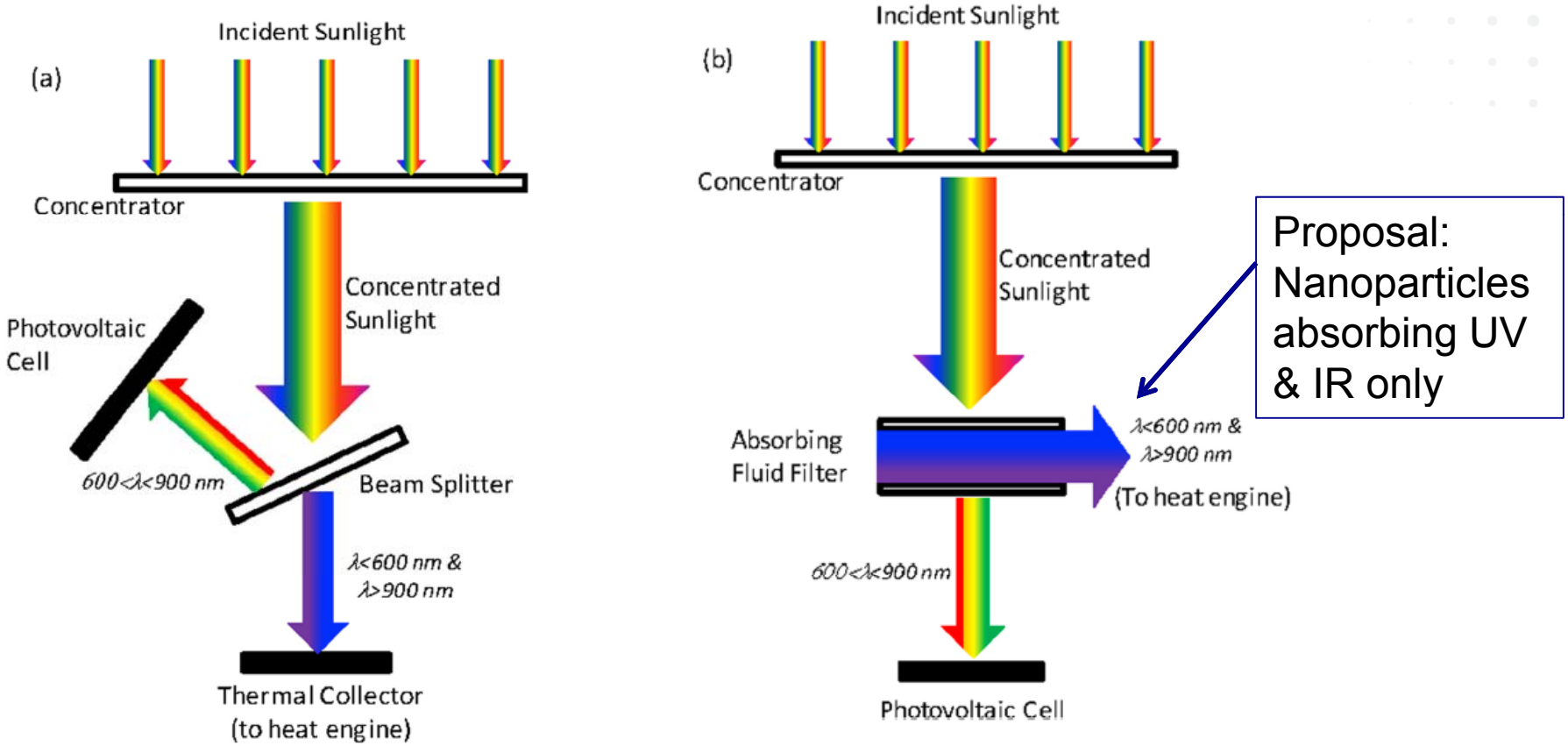
- Pro of examples:
  - Illuminate the concepts
  - Provide numbers (e.g., efficiency) for comparisons
  - Help identify flaws in our design space

- Con of examples:
  - We narrow our options and stop thinking outside-the-box
  - We get discouraged if the example is not disruptive to the present *status quo*
  - We consciously or subconsciously copy elements of flawed designs

- Advice:
  - See examples and forget them: you can do better

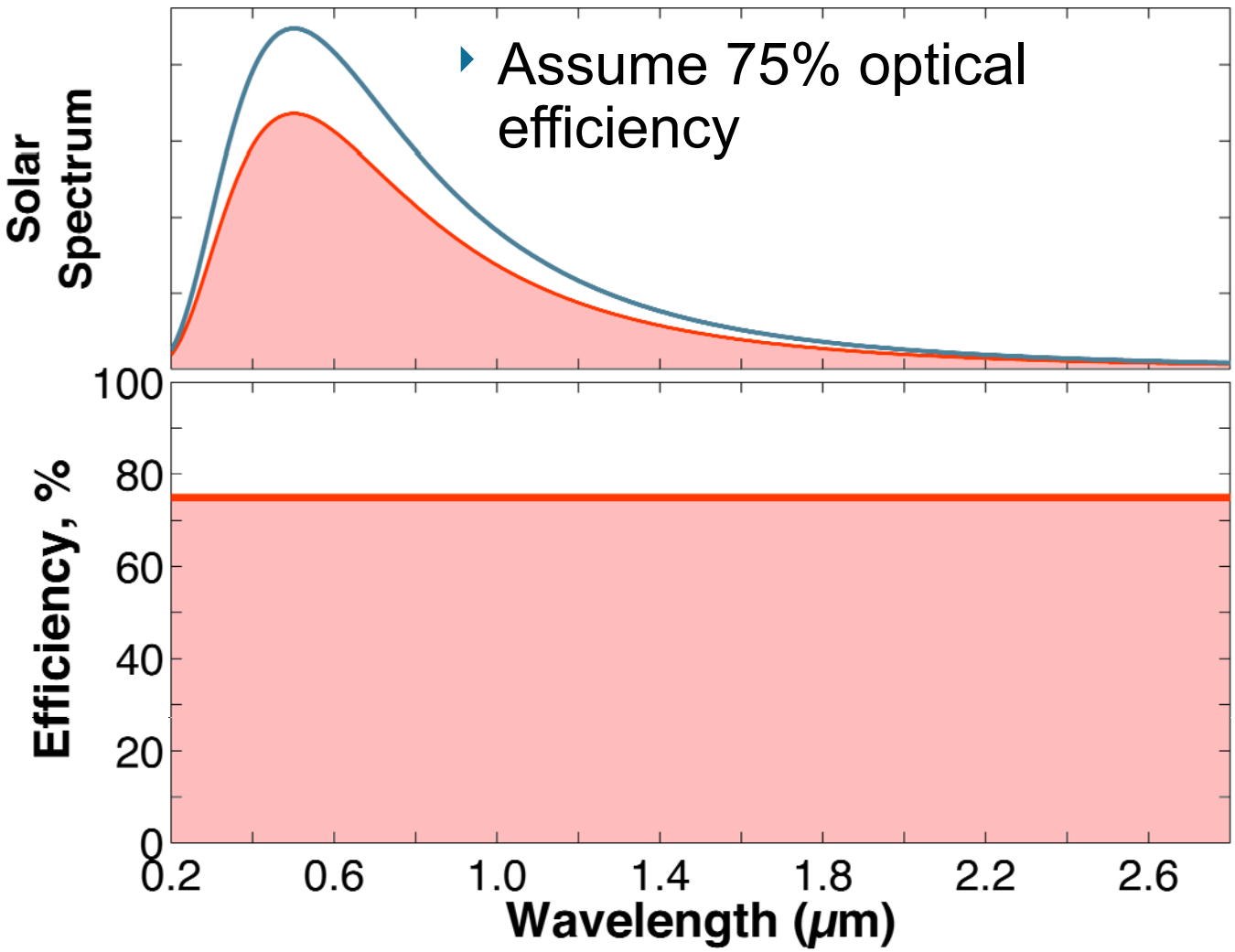
Example:
Spectrum-splitting to heat & PV electricity

- Detailed model of 200X system with efficiency >38% to electricity
  - 60% of this electricity is dispatchable



Otanicar et al, J. Solar Energy Eng, 2011

Cartoons of CSP + PV hybrids (approximate)



- Assume 75% optical efficiency

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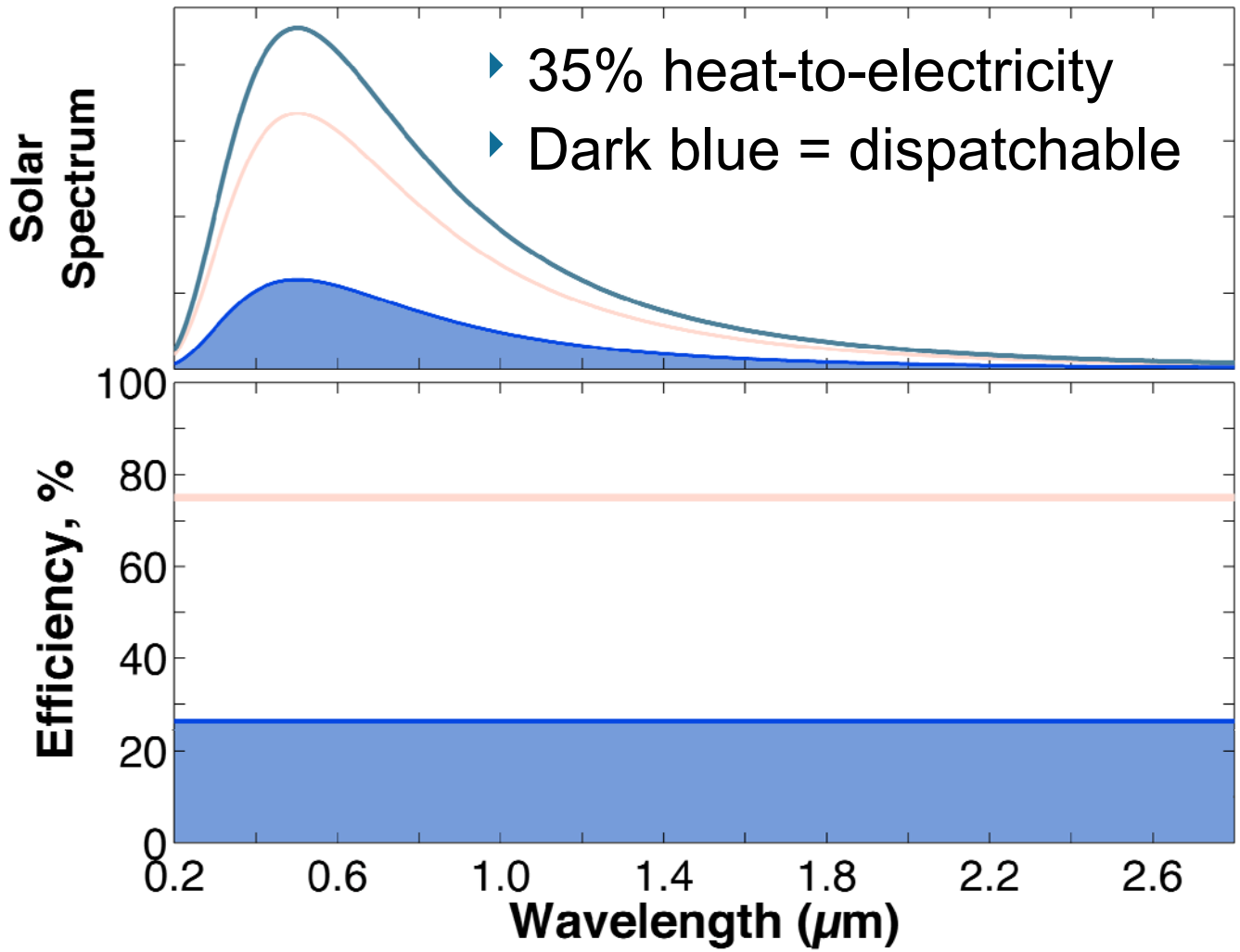

- 35% heat-to-electricity
- Dark blue = dispatchable

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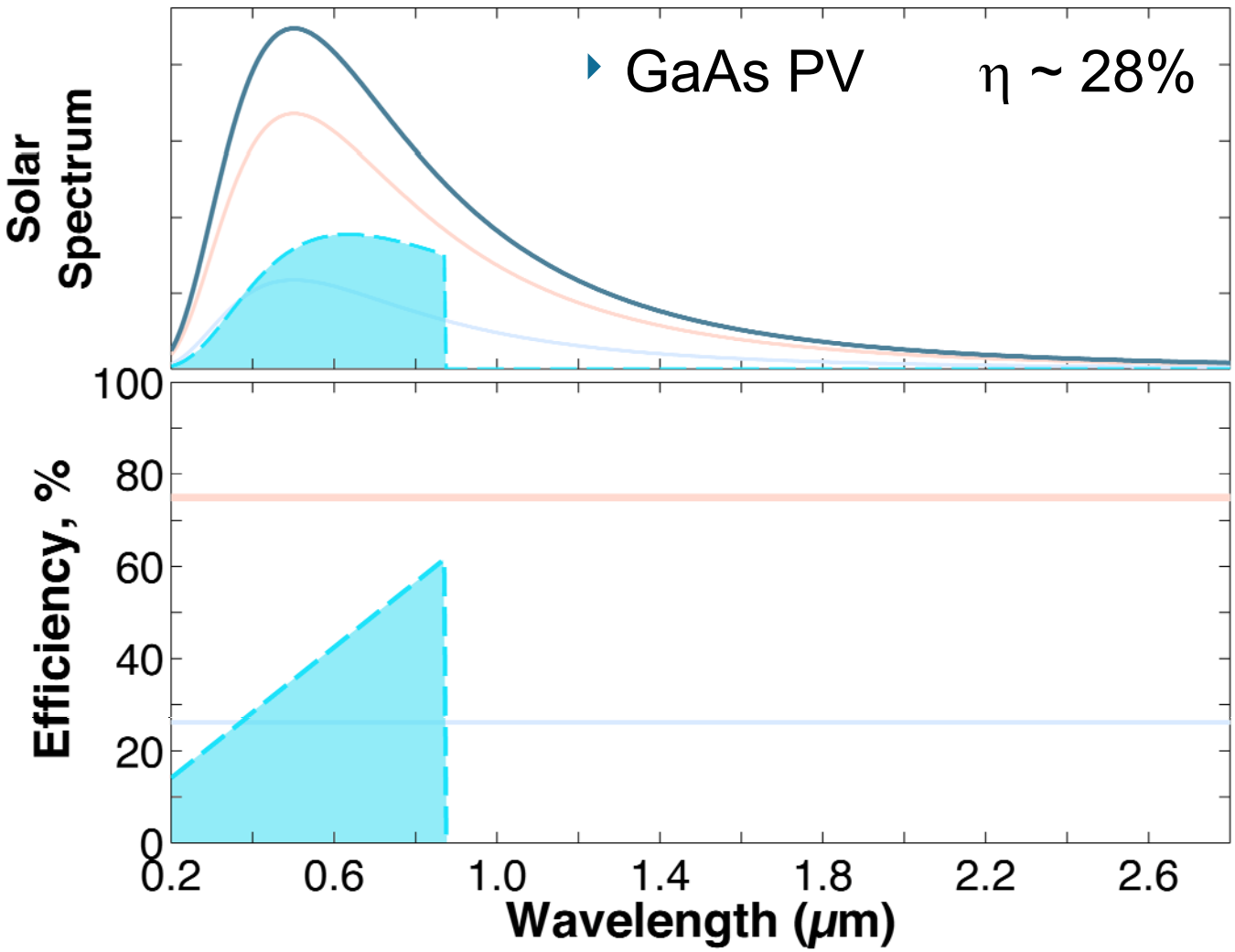

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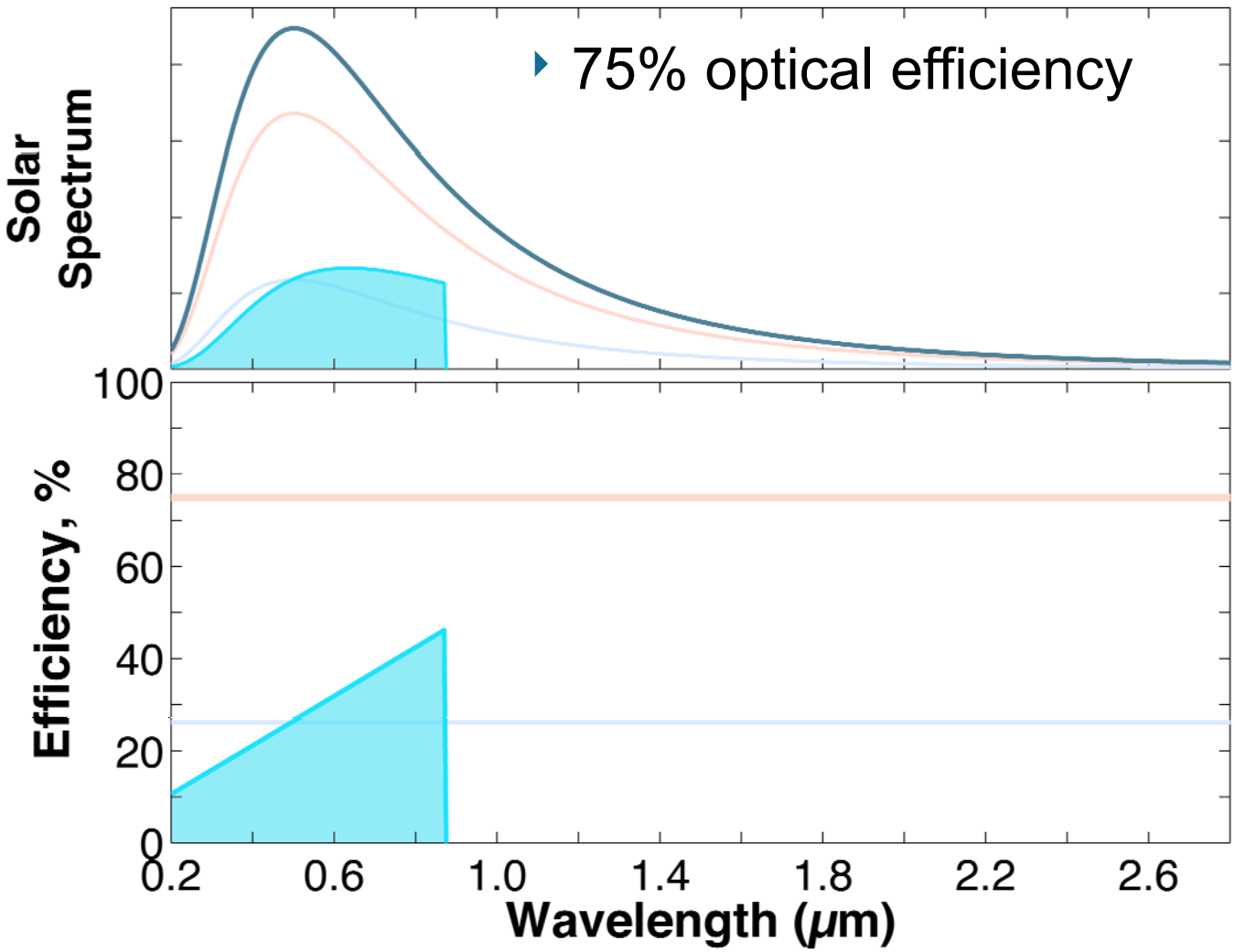

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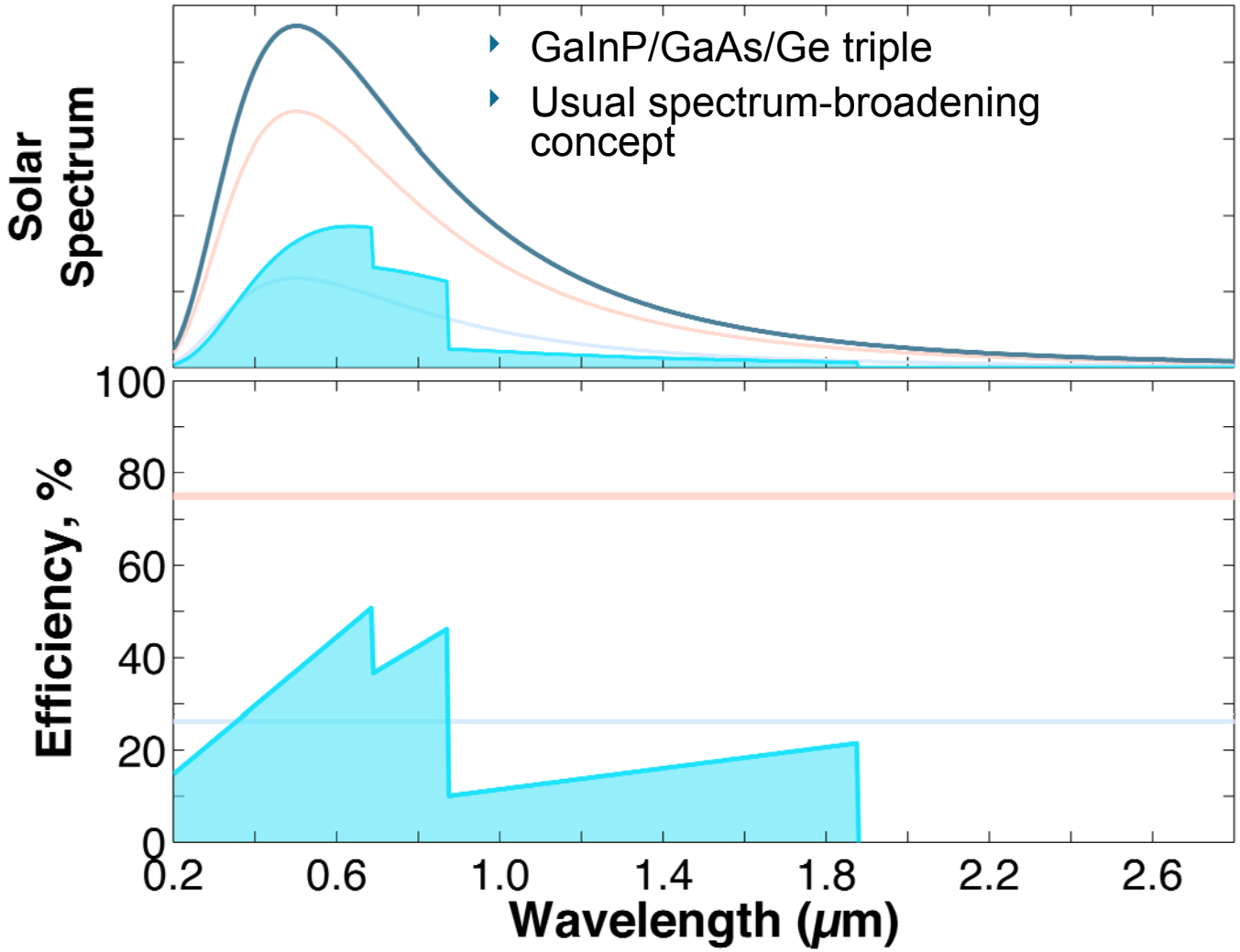

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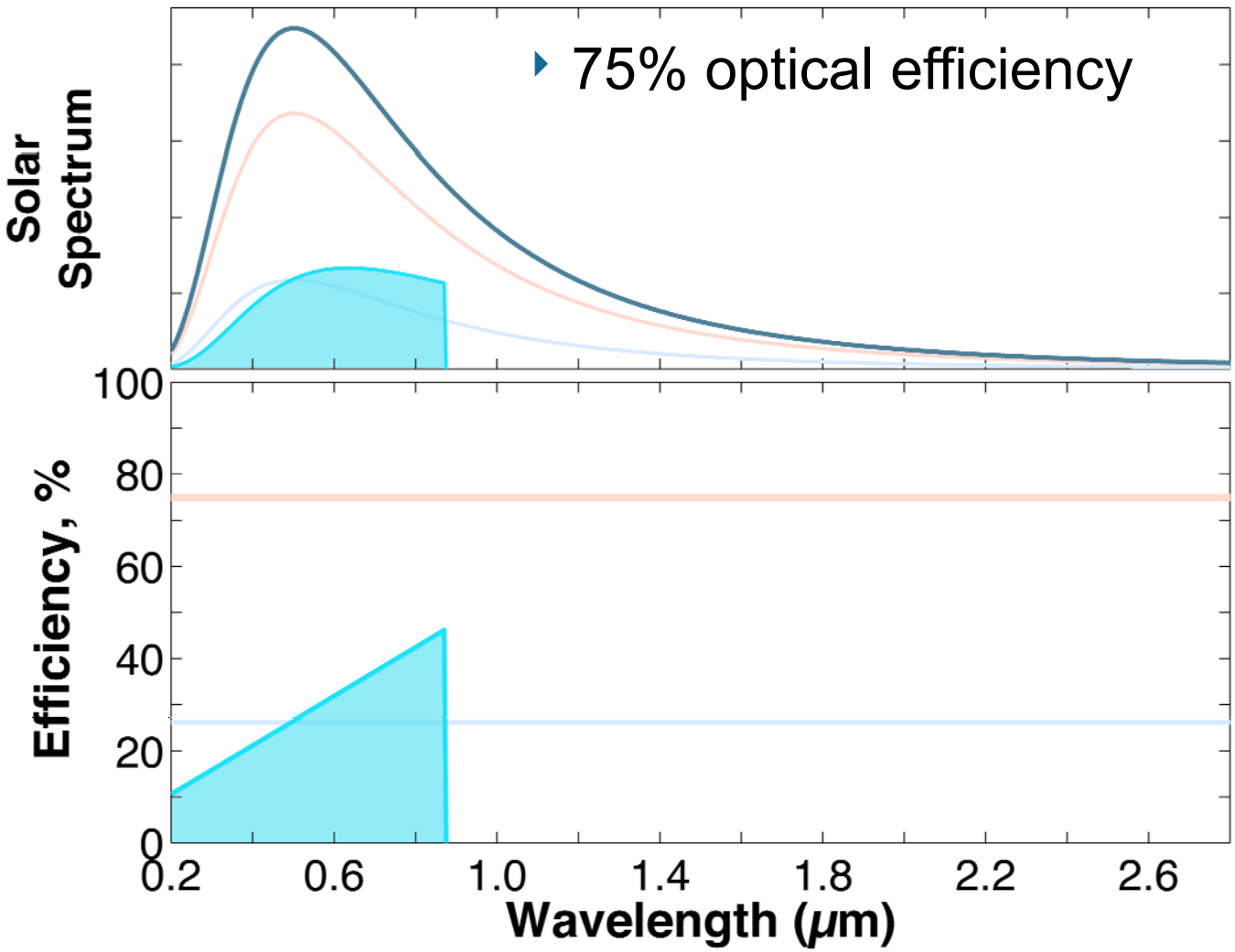

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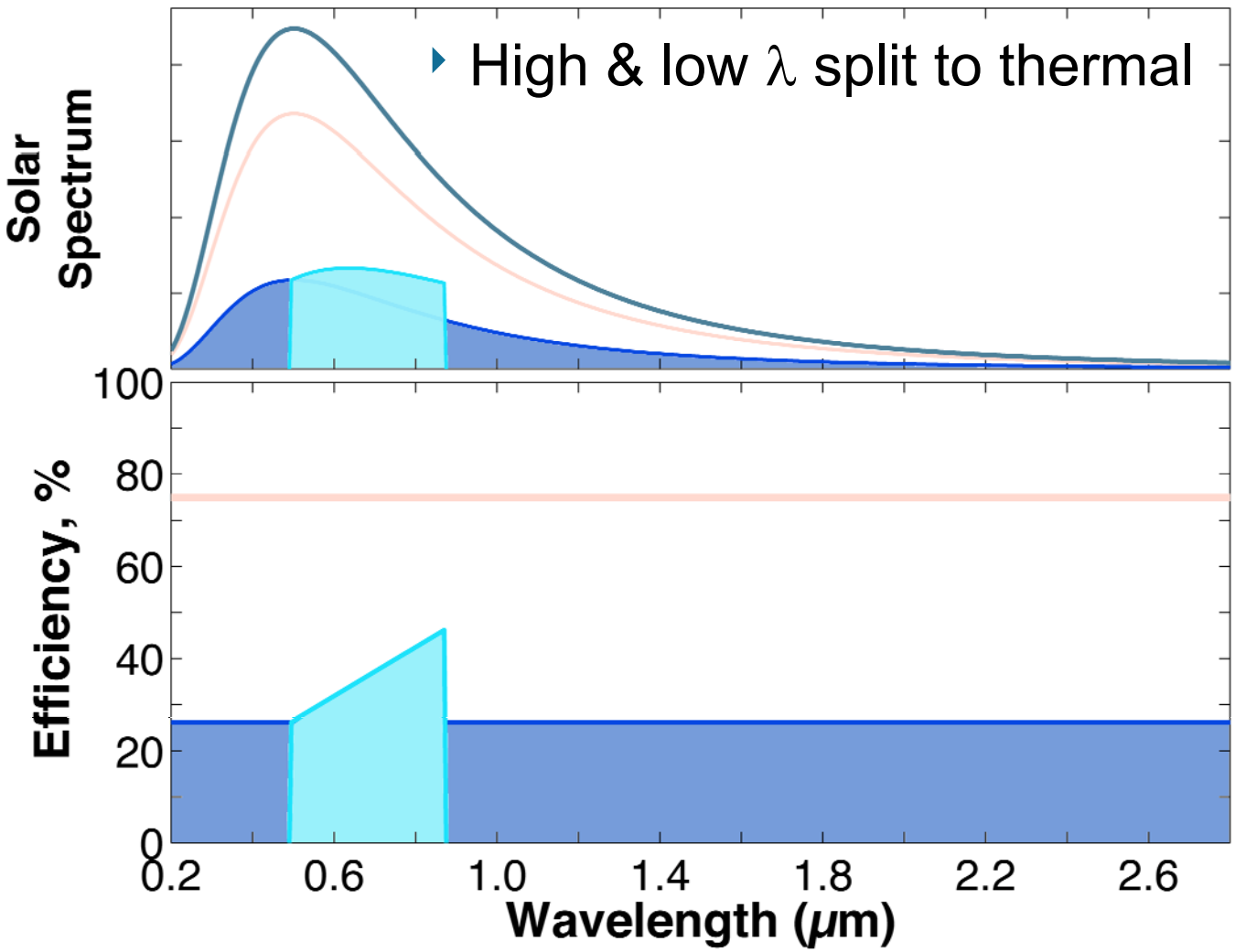

Otanicar et al, J. Solar Energy Eng, 2011

But there's another way…

- Collect losses in hot PV as useful heat

Concept explored: Otanicar et al, (ASU) JAP, 2010
Broderick et al (MIT) MRS Fall 2012

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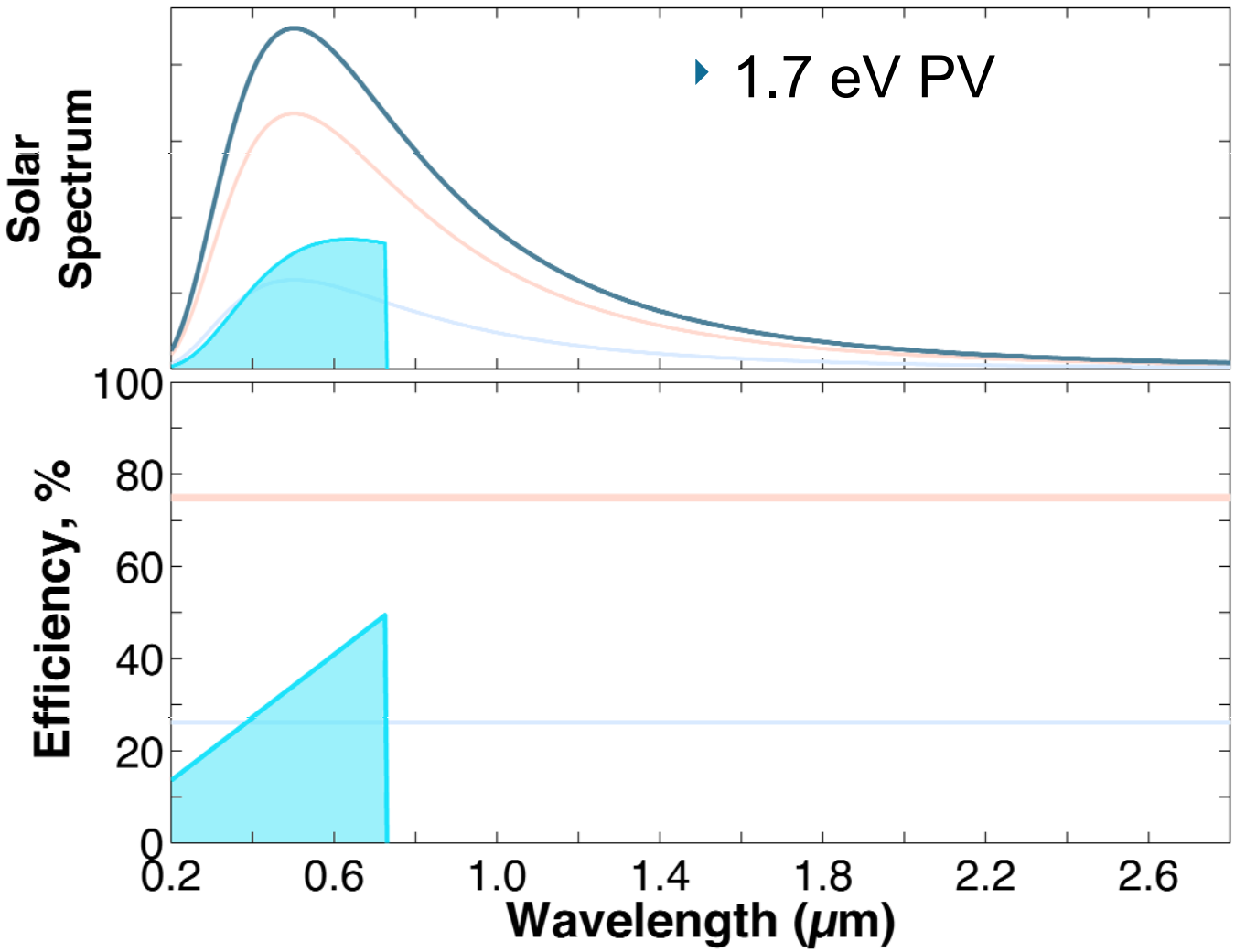

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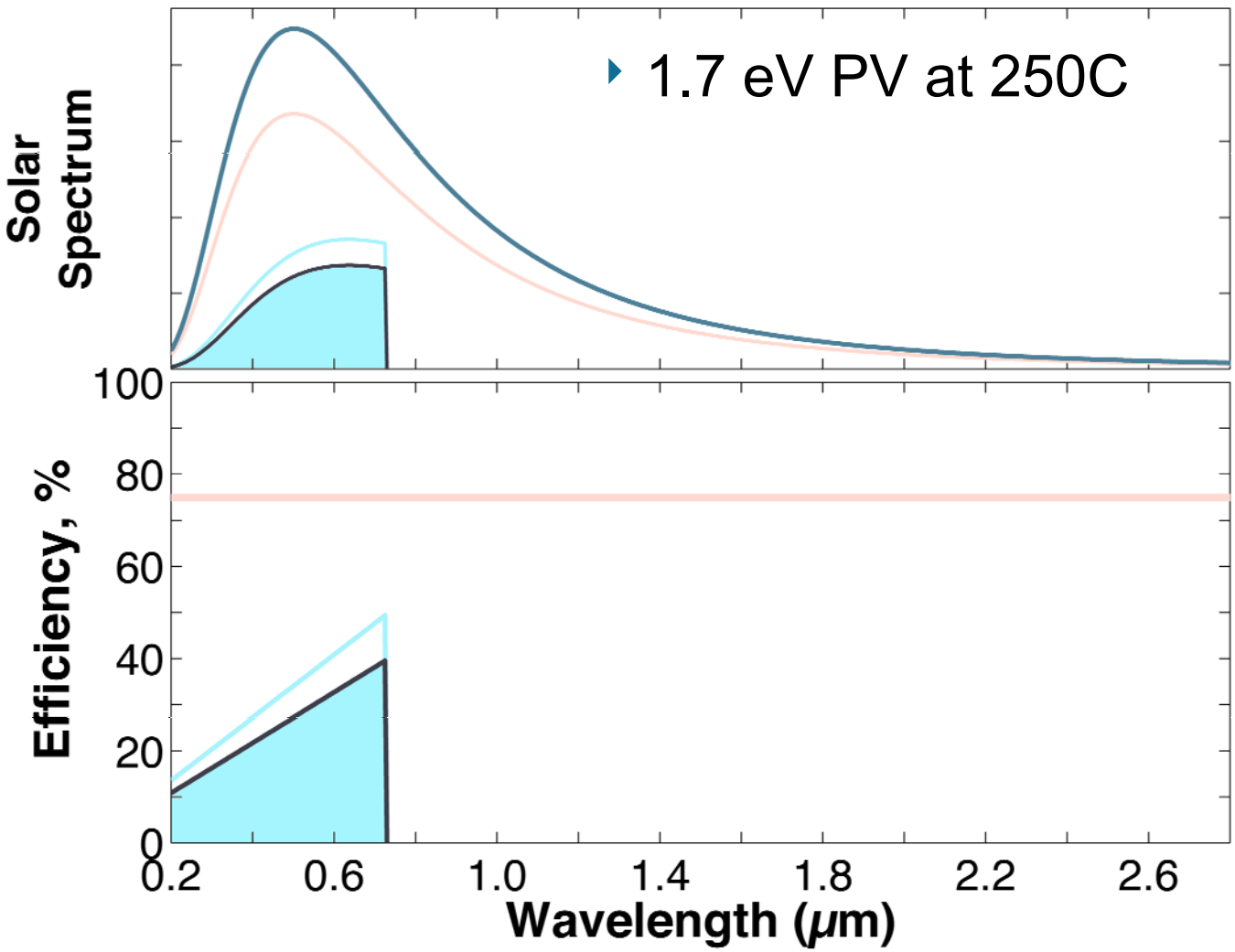

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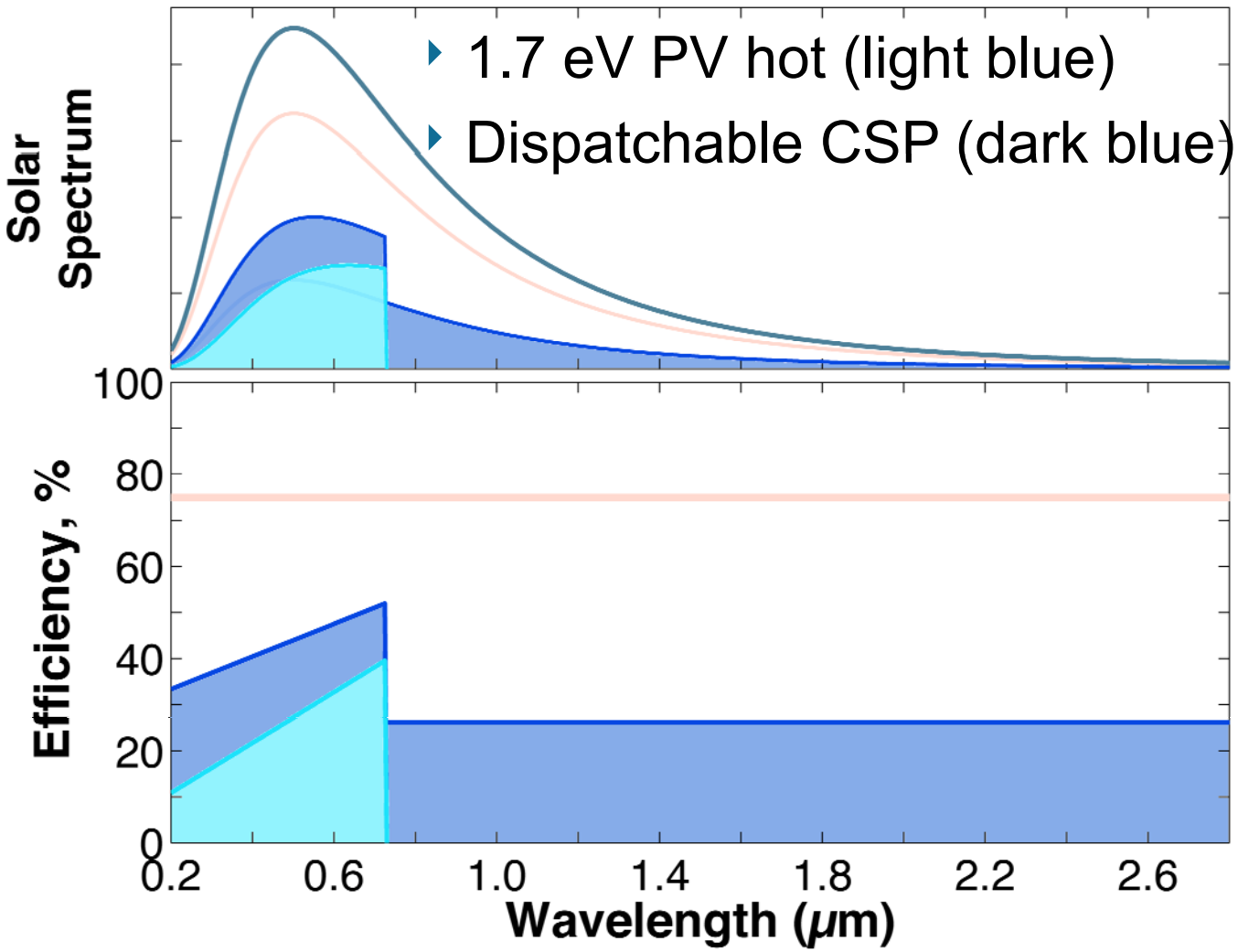
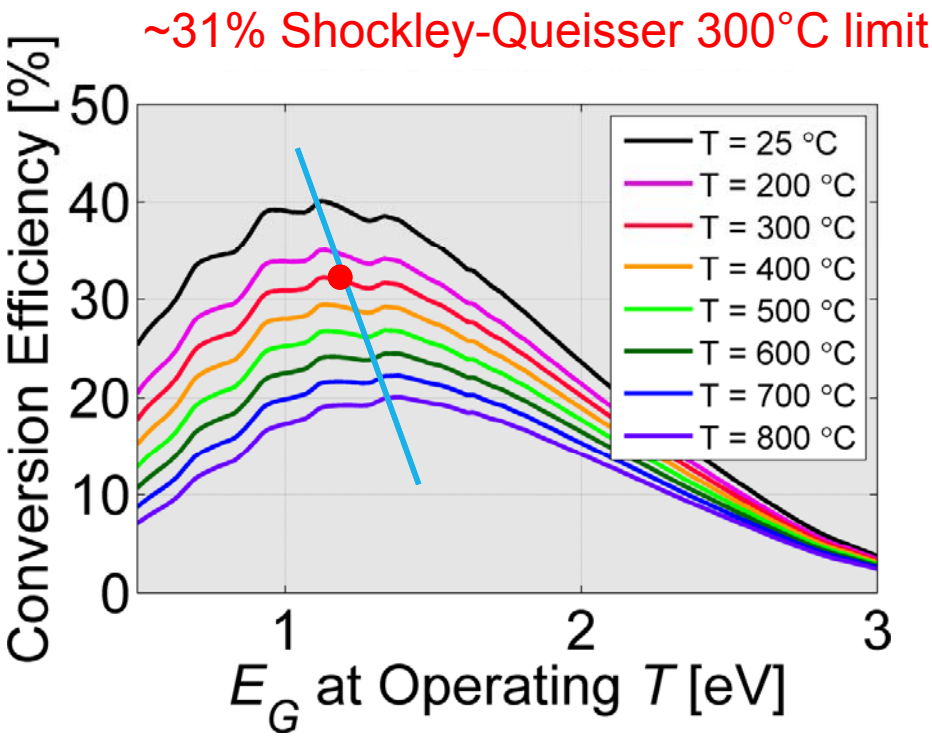
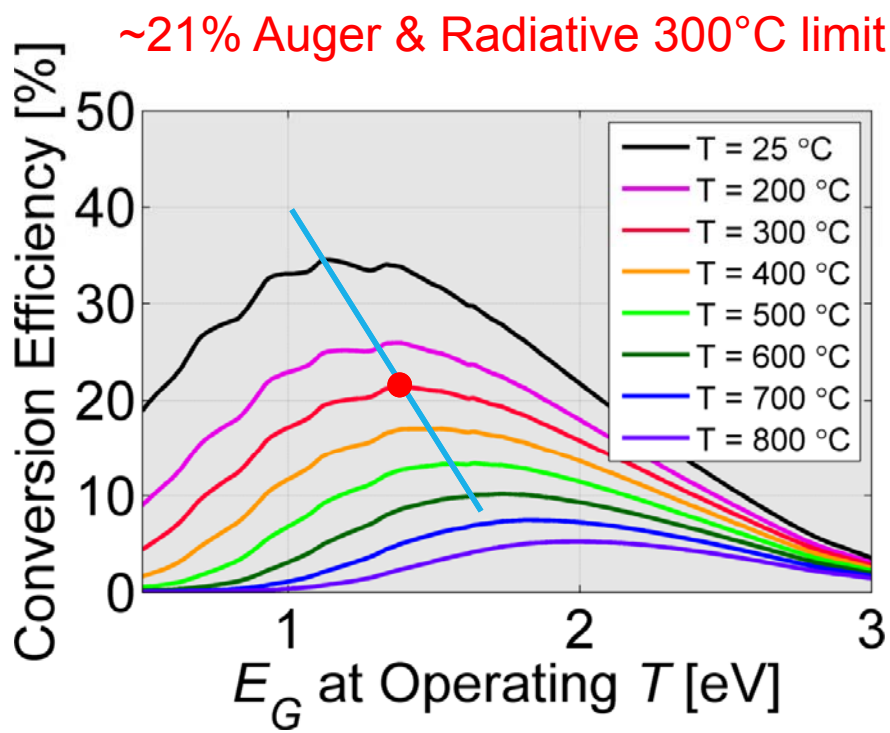


Single-junction PV high T performance limits

Wilcox & Gray, unpublished

- Under 500X concentration:

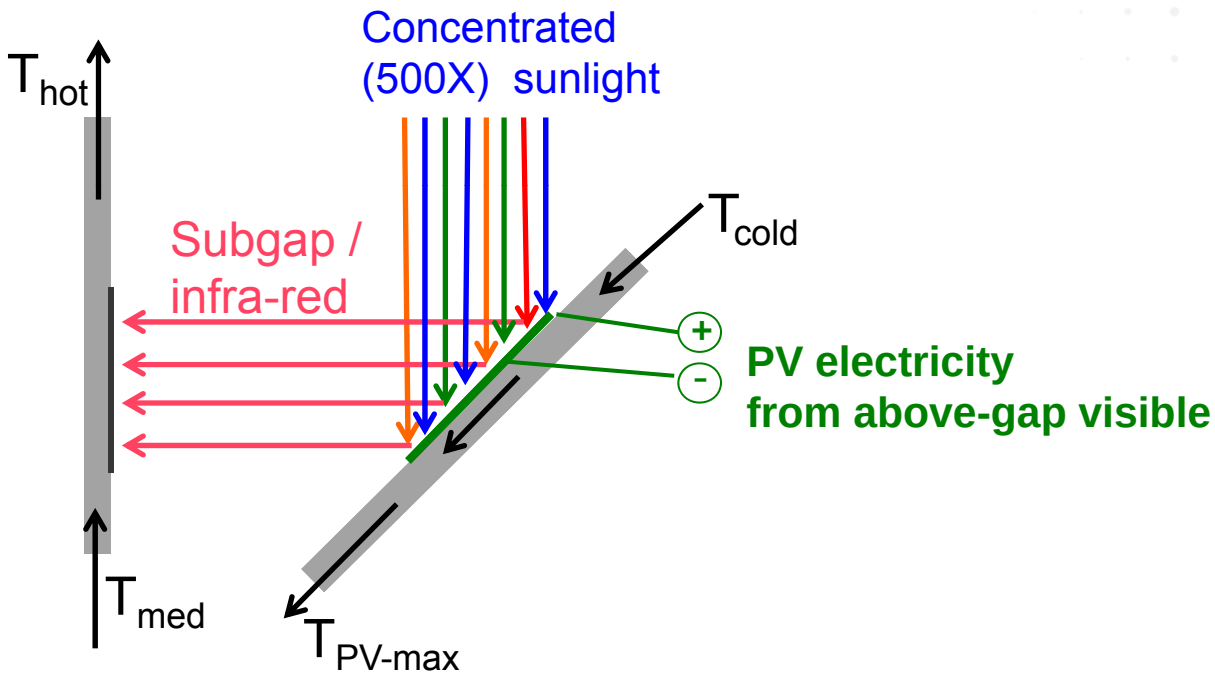




- Higher efficiency likely with 2 junctions
- High T PV market entry points in the “spillage” zone of CPV?

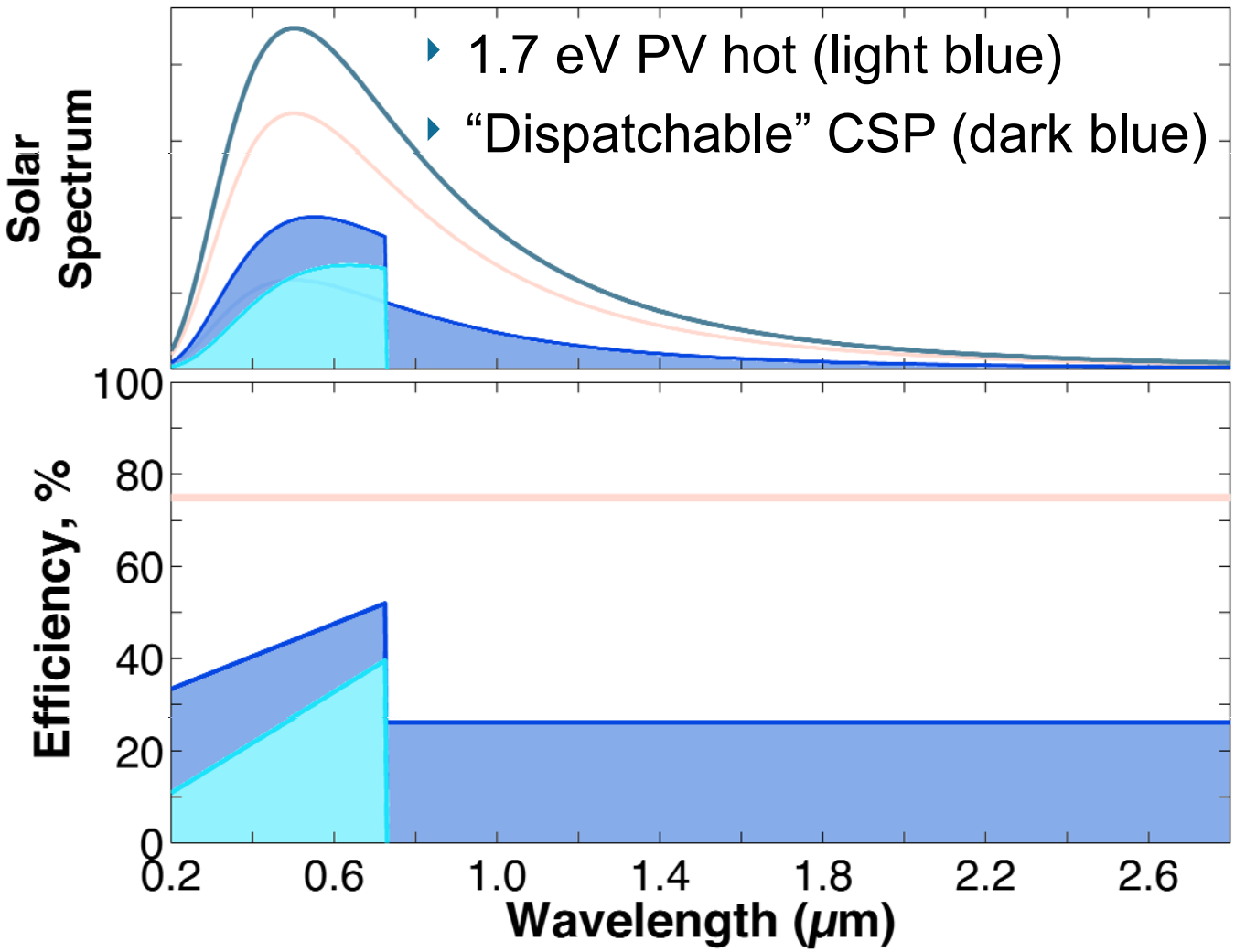
Example:
Lost PV heat collection with spectral splitting

- Single aperture collector at 500X for 30 - 40% solar-to-electricity efficiency
  - Half of electricity dispatchable (from heat)
  - Low incremental cost over CSP



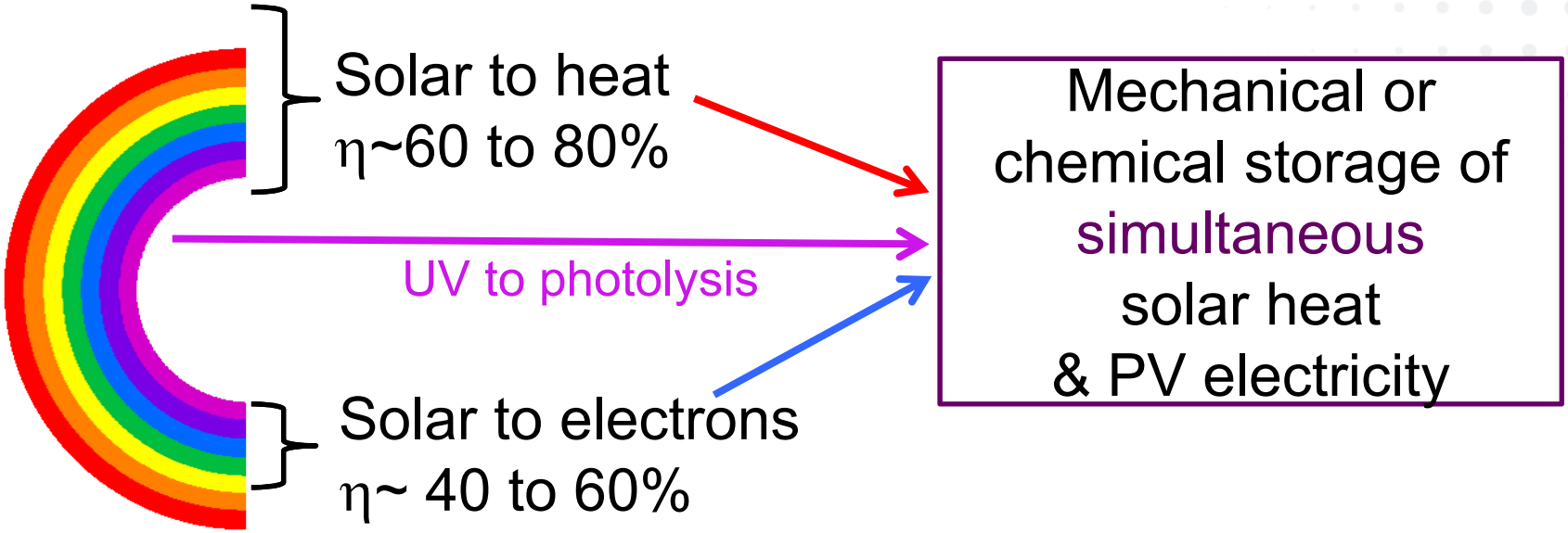
- Thermal losses from 250°C PV captured as heat, with T_{hot} ~ 300 °C
- Thermal model based on CSP today; PV model conservative

Instant Replay - Cartoon



Solar heat and electricity for storage

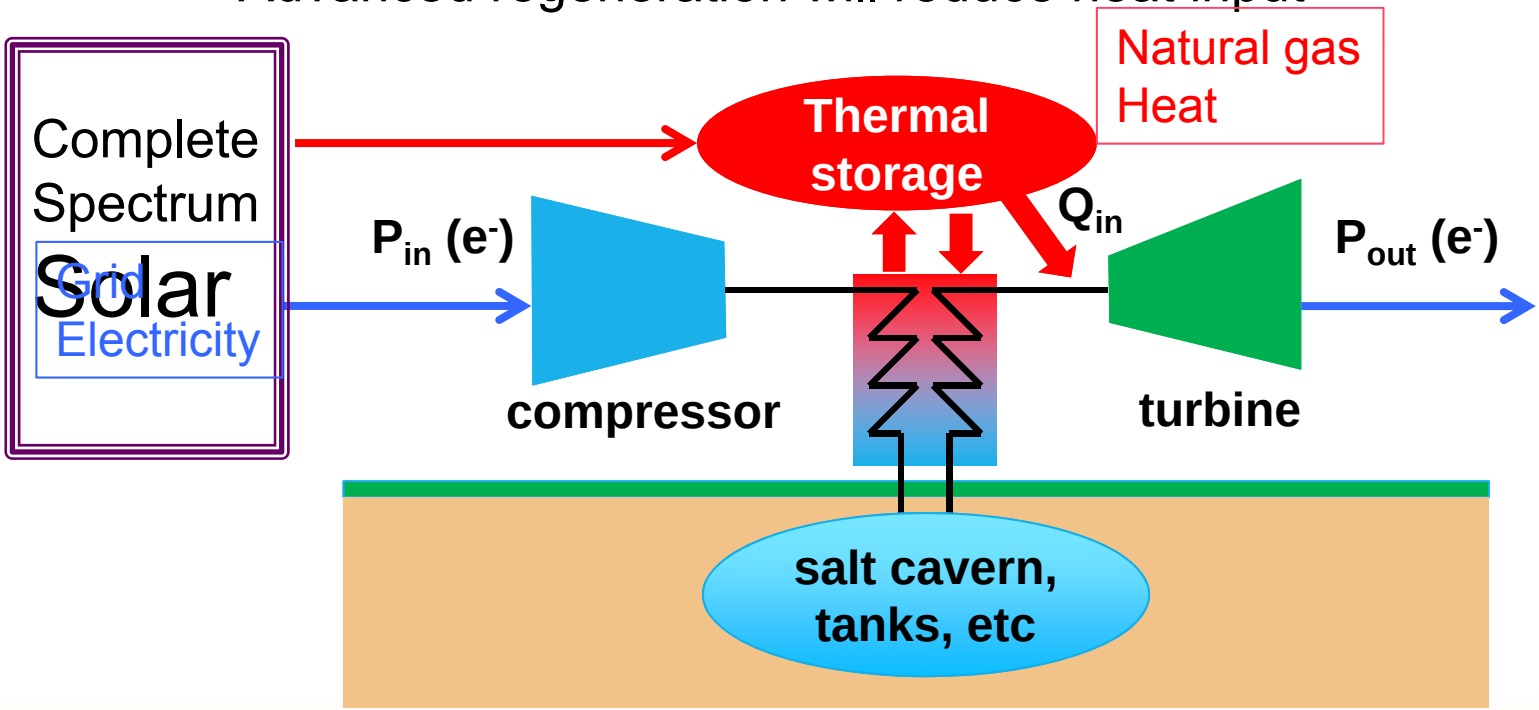
Integration for better spectrum usage:



- Optimize Heat/Electricity Ratio for storage (& efficiency)

Mechanical storage example: Compressed Air

- Fielded CAES system for grid electricity storage (PowerSouth)
  - Natural gas combustion for heat
- Roundtrip electricity efficiency of 40% (advanced ~ 70+%)
  - Heat:Electricity input ratio is 1:2
    - Advanced regeneration will reduce heat input



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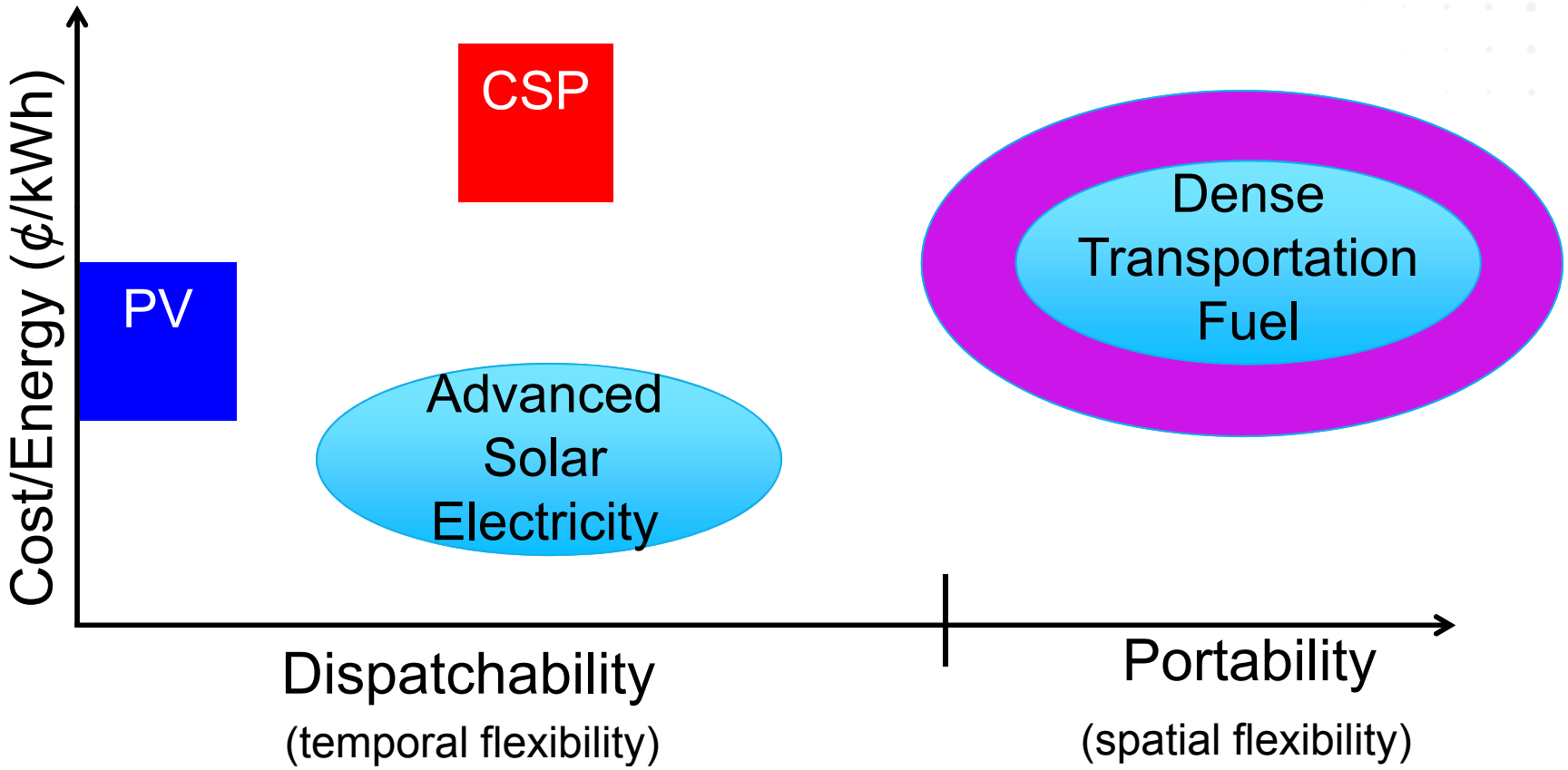
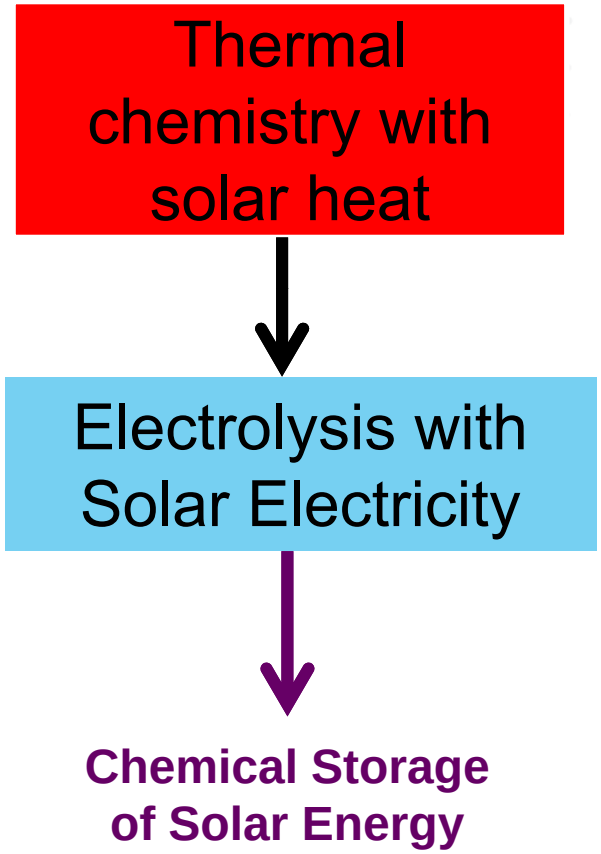


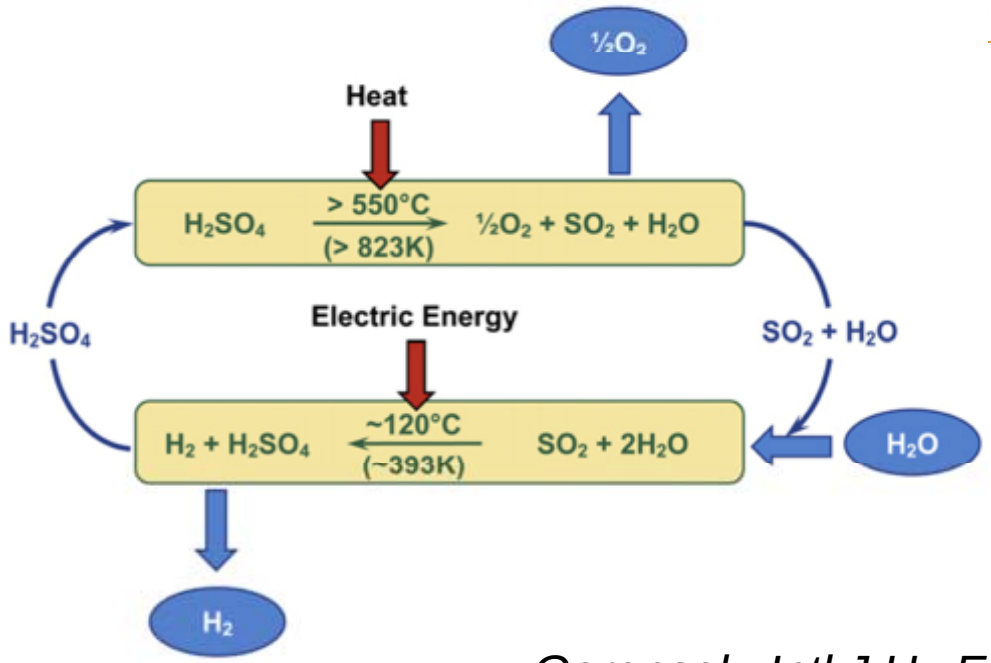
“Hybrid” thermochemical cycles

- History
  - R&D for solar or nuclear
  - Usually H_2 for Fuel Cell
- Status today:
  - Need high-grade (600 - 900°C) heat
  - Generally need more heat than electrical energy
  - Can hybrid cycles make products other than H_2?



Perret, DOE-EERE STCH Report, 2011
DOE Solar Thermochemistry Research

Example: Hybrid-sulfur hybrid cycle



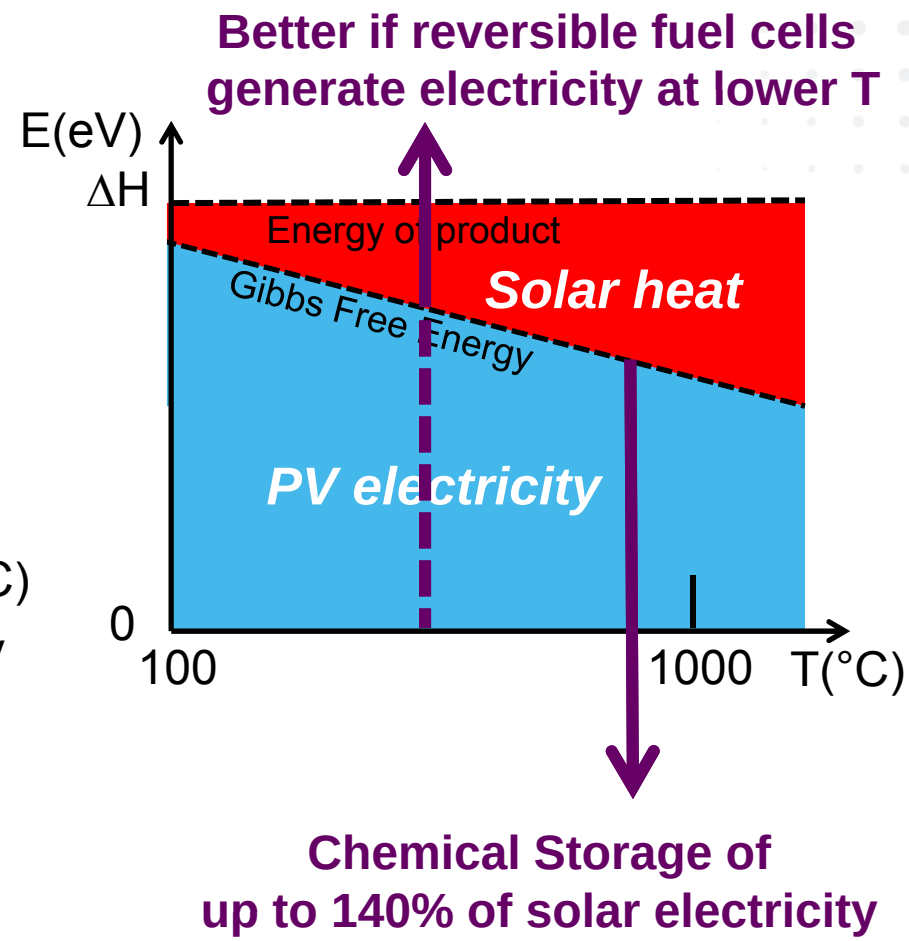
Gorensek, Intl J Hy Energy, 2012

- Thermodynamic efficiency ~ 50%
  - Heat:Electricity ~ 3:1
  - Are energetic chemical products more valuable in transportation?

Examples: High temperature electrolysis

$$\Delta G = \Delta H - T\Delta S - T[Nernst]$$

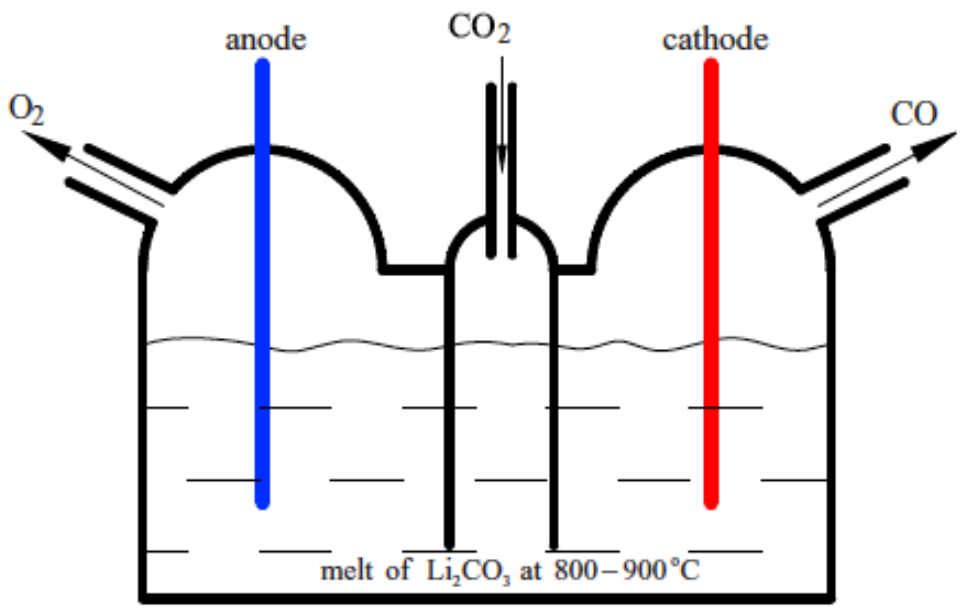
- History
  - Reversible solid-oxide fuel cell
    - H_2 and/or CO
  - Carbonate electrolysis to CO
- Status today:
  - Requires high-grade heat (600 - 900°C)
  - Uses more electricity than heat energy



Example: Carbonate electrolysis at >900°C

- Electrolysis of Li_2CO_3 to CO at ~ 0.9 V
  - ~2/3 of room T requirement
  - Electrolyte Regeneration: $Li_2O(\text{dissolved}) + CO_2(\text{gas}) \rightarrow Li_2CO_3(\text{molten})$

Licht et al, J Phys Chem 2010
Kaplan et al, JECS 2010



- Thermodynamic efficiency > 80% at 100 mA/cm^2
  - Heat:Electricity ~ 1:3

The pros & cons of showing specific design examples

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- Advice:
  - See examples and forget them: You can do better

Workshop goals

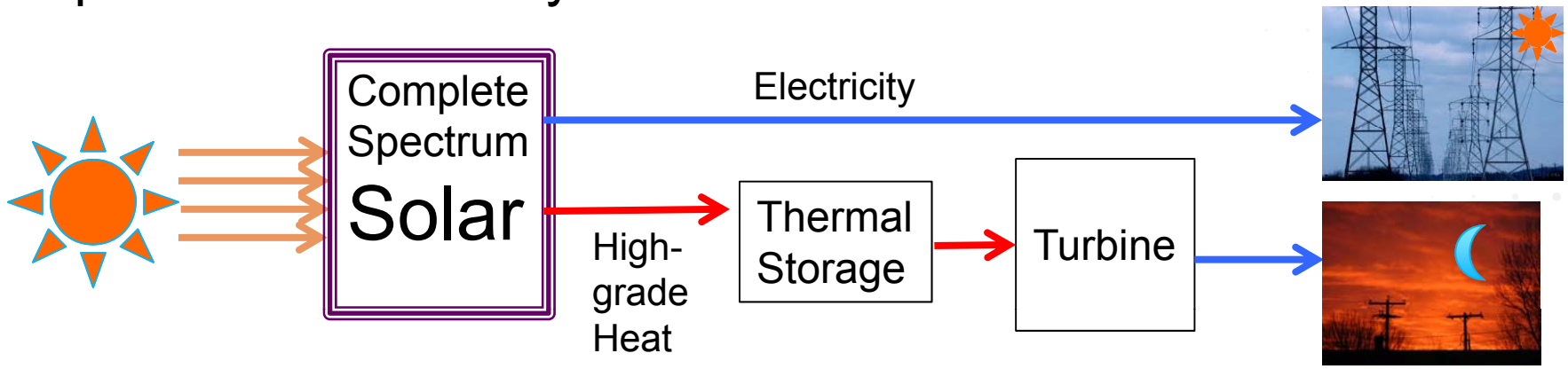
- Identify critical technology advances to open a disruptive new design space for solar with storage
  - New system designs
  - Optimized spectrum exploitation
  - Storage using heat, electricity & photons
- Encourage diverse technical communities to think together
  - Get out of your sub-field and talk
- Inform ARPA-E
  - On the strengths and weaknesses of this technology space
  - Refine our thinking about disruptive opportunities in solar

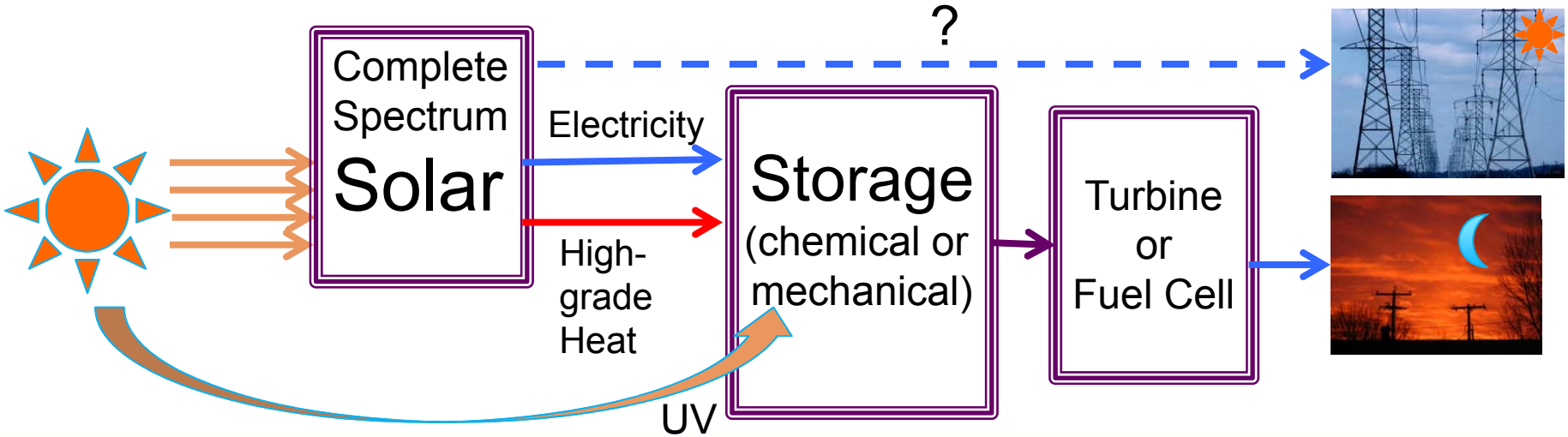
Format of Workshop

- Intro talks on a few areas of interest
- Facilitated breakouts with discussion questions
- ARPA-E facilitator
    - Ensures many voices heard
    - Organizes report-back to larger group
  - ARPA-E note-taker

Example ARPA-E Workshop Interest Areas

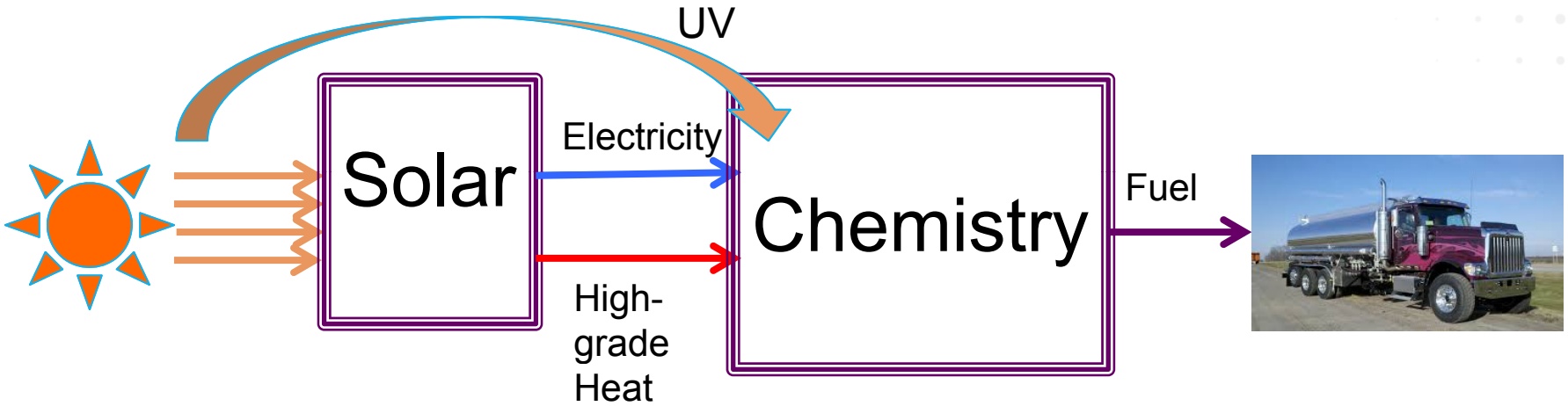
- Dispatchable electricity





Example ARPA-E Workshop Interest Areas

- Portability (dense transportation fuel)



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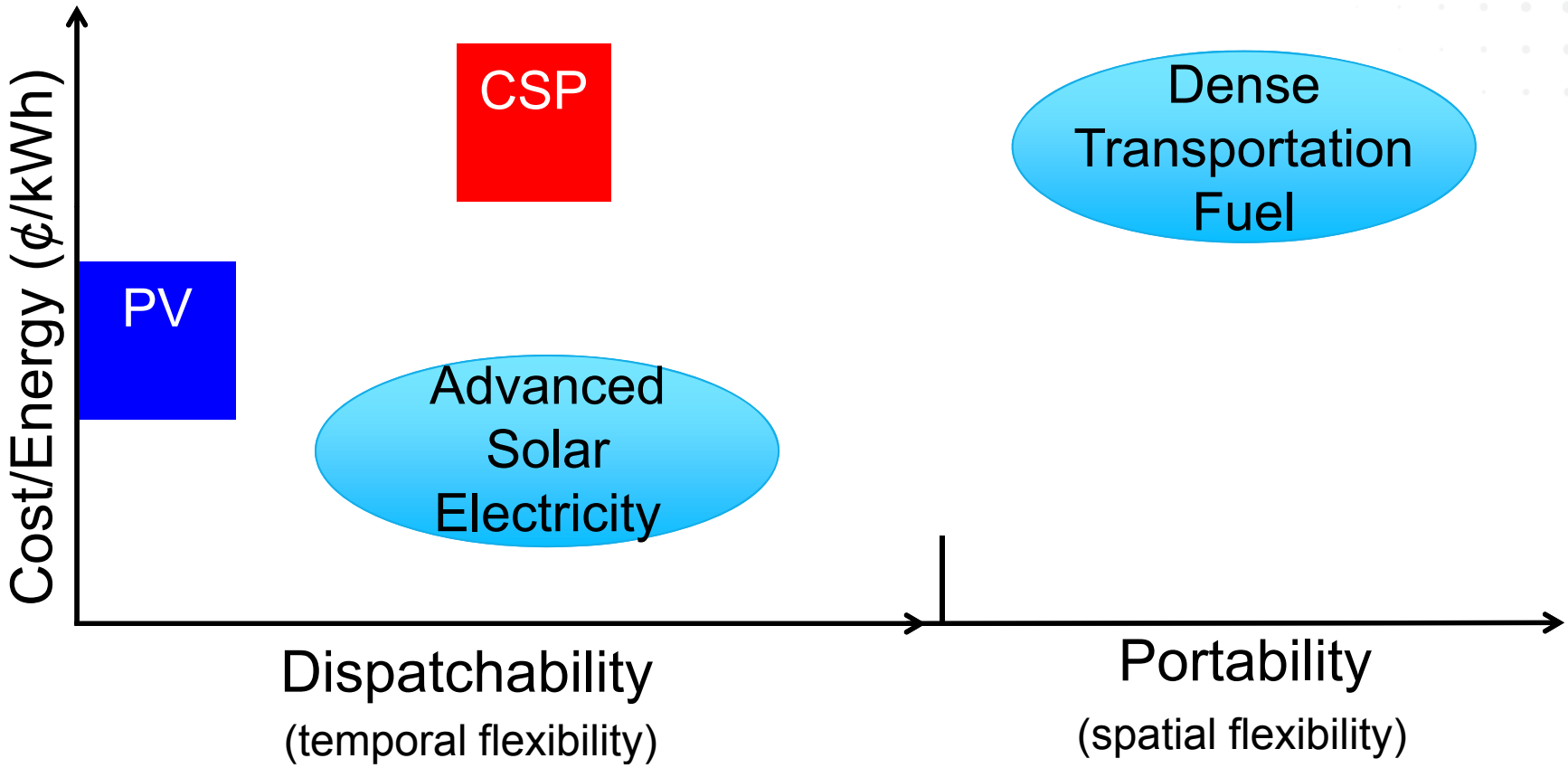

You are at ARPA-E today:

Think Innovative

Think Disruptive

Change What's Possible

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