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CSP-H₂ System Study Status Update

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Agenda

- Draft final brief with updated results Scott
- Draft report outline Scott
- Brainstorming session - Discussion/Questions All

Project background

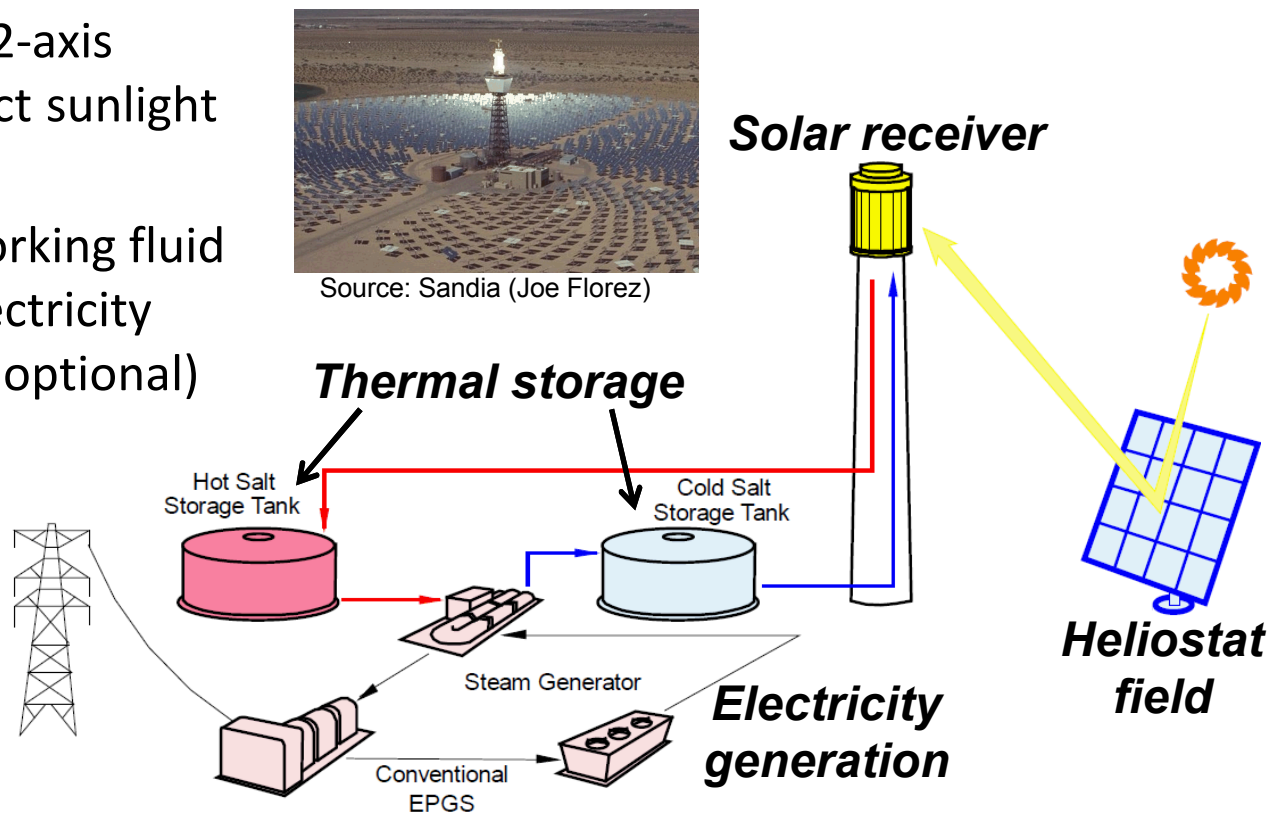
- Project goal
 - Explore pathways for integrating concentrating solar power (CSP) and solar hydrogen production → Do synergies exist that could reduce costs?
 - Identify potential opportunities for SunShot-FCTO collaboration
- Scope: Process-level integration of CSP and H₂ production
 - No consideration of H₂ for energy storage
 - No transportation/geographical considerations (e.g., benefits of co-locating H₂ production near industrial users)
- Modeling and analysis approach
 - Leverage existing models and data related to CSP and solar H₂ production → Simplify when possible (Our goal is NOT process optimization)
 - Identify important performance drivers and fundamental conditions that favor CSP-H₂ integration
 - Understand key uncertainties and ensure robustness of conclusions

Modeling approach leverages previous analyses of CSP and H₂ production

- CSP: Published reports and models developed at Sandia
 - Power conversion calculations and reliability analysis
 - Capital and O&M cost estimates → Levelized cost of electricity (LCOE)
 - Future cost reduction and performance targets
- Hydrogen production: H₂A models
 - Discounted cash flow analysis based on conversion efficiency and capital, O&M, and materials costs
 - Output is cost of H₂ per kg
- Key relationships were extracted and represented in a simplified Excel-based model
 - Improved consistency across processes
 - Reduced complexity → Enhanced analysis efficiency/flexibility

Concentrating solar power (CSP)

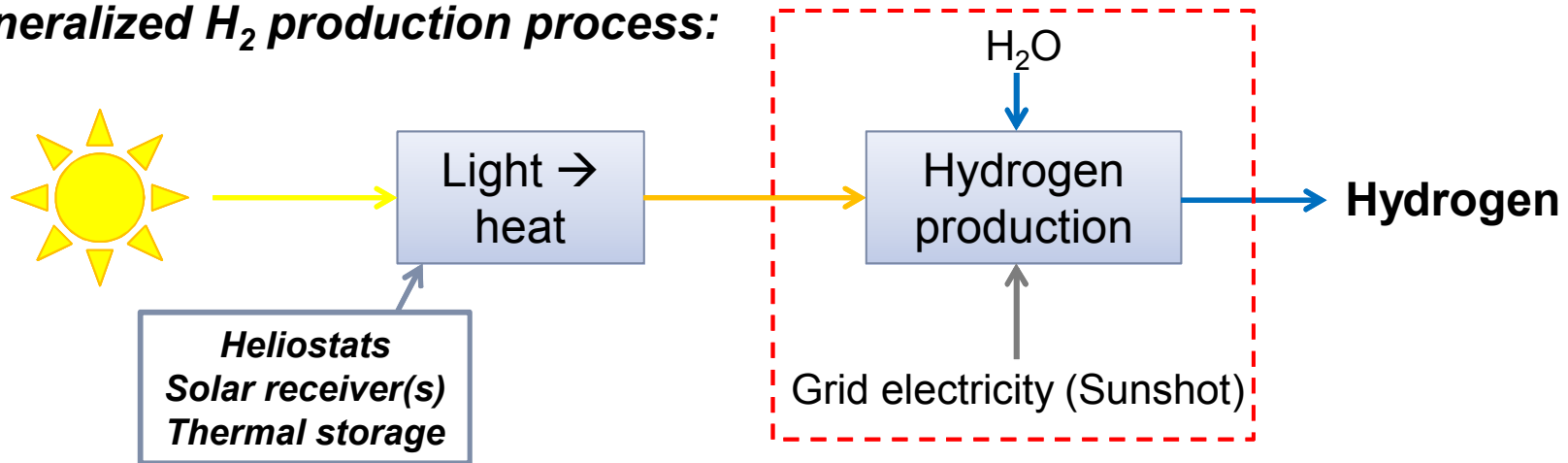
- Heliostats (mirrors with 2-axis directional control) reflect sunlight onto a solar receiver
- Heat is absorbed by a working fluid and transferred to an electricity generation unit (storage optional)
- Approximate capital cost breakdown:
 - Heliostats: 30-40%
 - Solar receiver: 20-25%
 - Storage: 20-25%
 - Electricity gen: 15-20%



Baseline CSP plant: Power Tower configuration with molten salt thermal storage and subcritical Rankine cycle electricity generation
→ 2010 Sandia estimate: \$0.15/kWh; SunShot goal: \$0.06/kWh

Current H2A analyses assume grid electricity

Generalized H₂ production process:

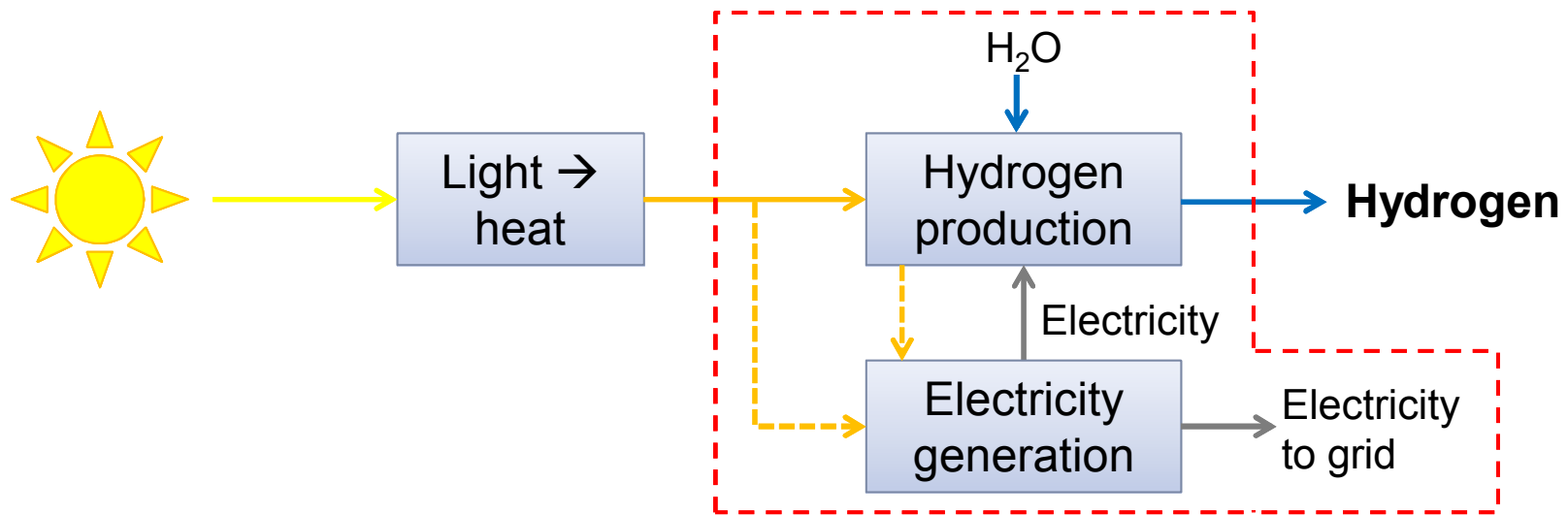


$$H_2 \text{ cost} = \frac{(annualized \text{ capital cost})_{no \ e^- \ gen} + (O\&M \ cost)_{no \ e^- \ gen} + \boxed{electricity \ cost}}{(annual \ H_2 \ production)_{no \ e^- \ gen} (plant \ availability)_{no \ e^- \ gen}}$$

Determined by H₂ production efficiency, η

CSP and H₂ production are treated as separate, non-interacting processes in H2A

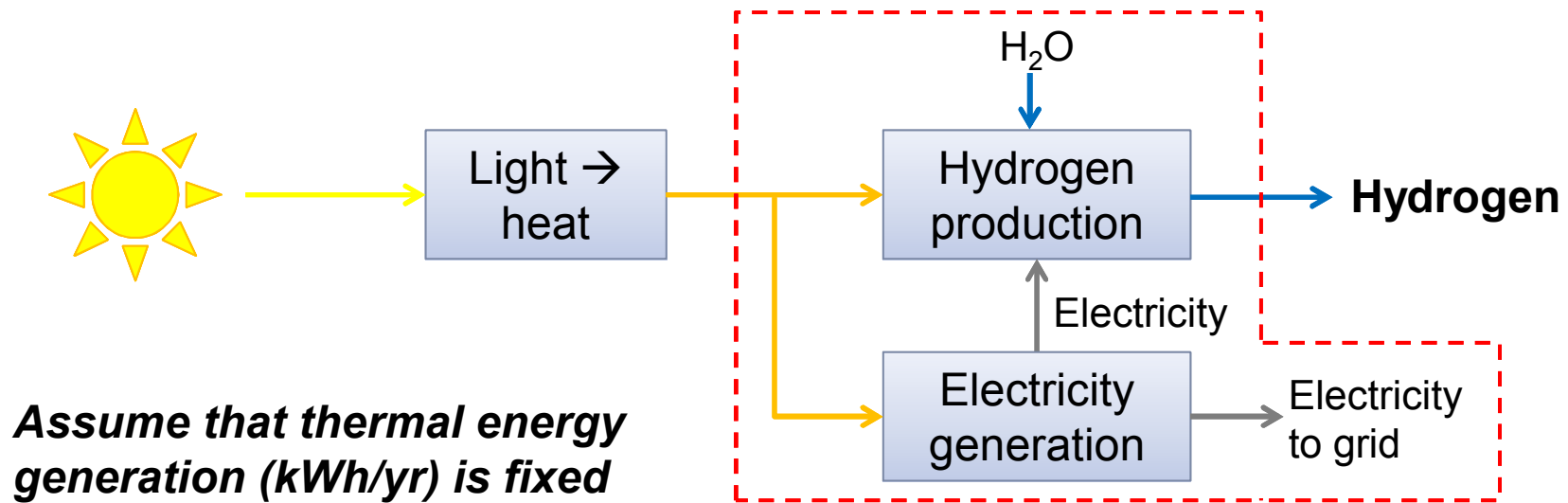
Extend H₂ production cost calculations to include co-production of electricity



$$H_2 \text{ cost} = \frac{(\text{annualized capital cost})_{\text{with } e^- \text{ gen}} + (\text{O\&M cost})_{\text{with } e^- \text{ gen}} - \text{electricity revenue}}{(\text{annual } H_2 \text{ production})_{\text{with } e^- \text{ gen}} (\text{plant availability})_{\text{with } e^- \text{ gen}}}$$

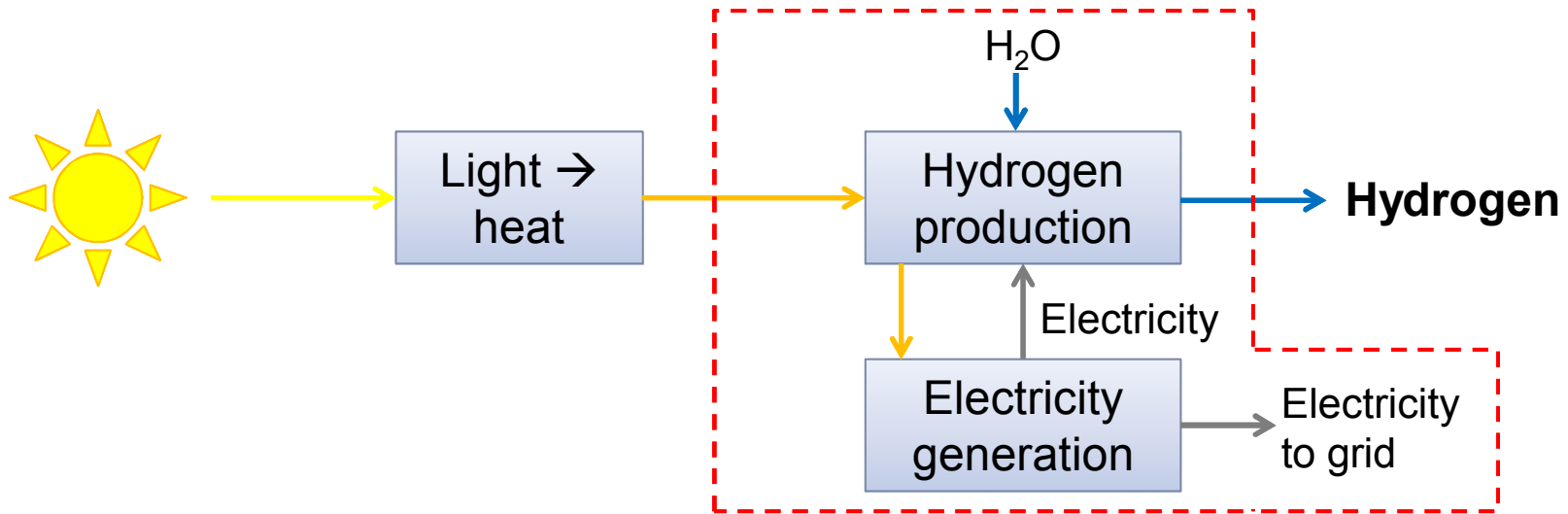
Including CSP plant will increase capital and O&M costs,
but electricity sales generate revenue

Diverting high-quality thermal energy to electricity generation yields no obvious benefits



- Economies of scale generally favor higher throughput for a given piece of equipment
- Simply diverting solar thermal energy to two processes (H₂ and electricity) will result in higher costs for both H₂ and electricity
 - Production of a single product (H₂ or electricity) will be favored

Investigate opportunities for integrating H₂ production and CSP processes



Key question to ask for each process: Are there potential synergies between the processes that could be leveraged to compensate for unfavorable economies of scale?

- Waste heat streams
- Byproducts → Feedstocks

Thermal energy is a major cost → Focus on heat streams for CSP-H₂ integration

Three scenarios for integration of CSP and H₂ production were analyzed

1. Baseline: CSP electricity coupled with polymer electrolyte membrane (PEM) electrolysis (low-T)
2. Elevated temperature (850 C) electrolysis integrated with a CSP plant
3. High temperature (1380 C) thermochemical (TC) H₂ production integrated with a CSP plant

Focus on power tower solar energy collection is in alignment with DOE CSP Office priorities (SunShot specifies 100 MW_e plant)

→ Compatibility with molten salt or falling particle receivers is a requirement for consideration of potential H₂ technologies

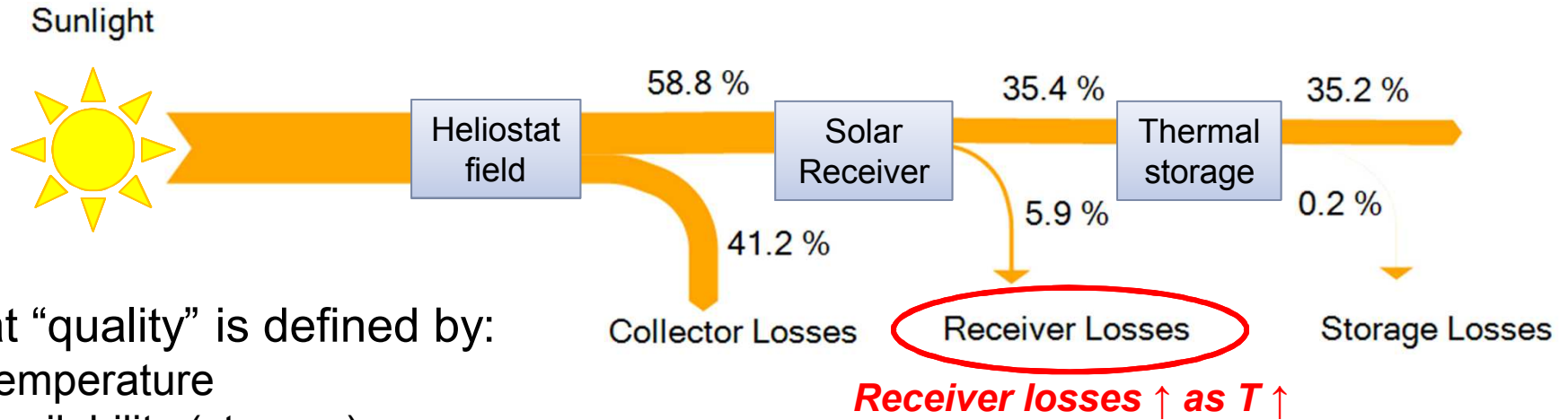
Key assumptions

- Ownership model
 - In the case of two integrated towers, assume that both towers are owned by the same entity
 - Sell electricity at wholesale price, account for revenue in H₂ cost

- Electricity prices
 - CA: \$0.134/kWh retail (industrial), \$0.042/kWh wholesale
 - AZ: \$0.066/kWh retail (industrial), \$0.035/kWh wholesale

- Equipment costs
 - For H₂ production: Costs from “Future” H2A worksheets
 - For CSP: Costs to reach SunShot target

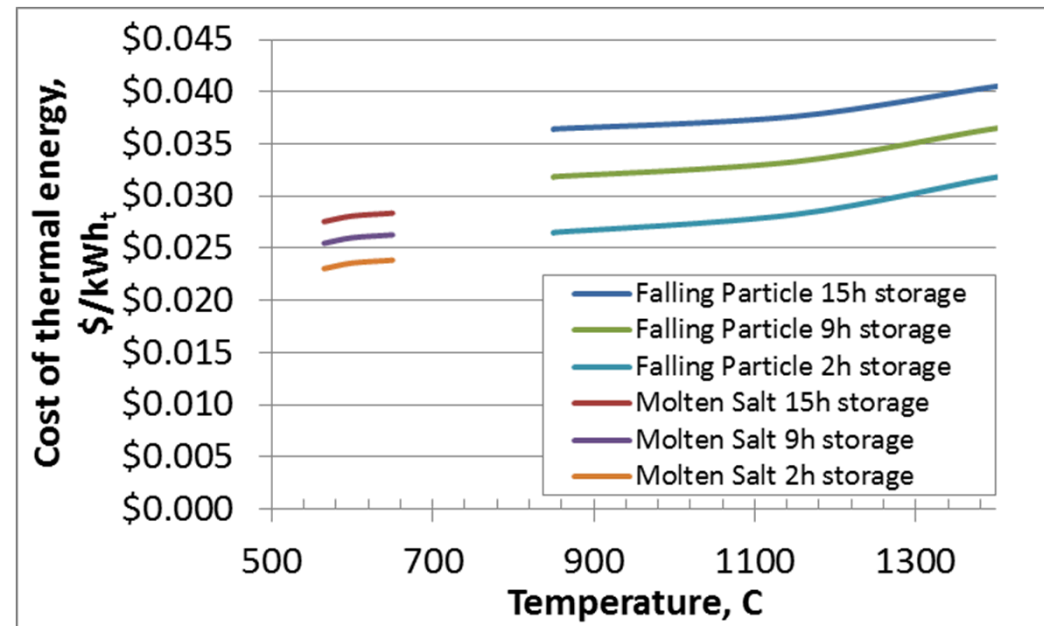
Heat as a “feedstock”



Heat “quality” is defined by:

- Temperature
- Availability (storage)
- Higher T may allow more efficient conversion to electricity or H₂, but “feedstock” is more costly
- As storage costs ↑, downstream capital costs ↓ and capacity factor of downstream components ↑

Solar thermal energy “feedstock” is a major cost

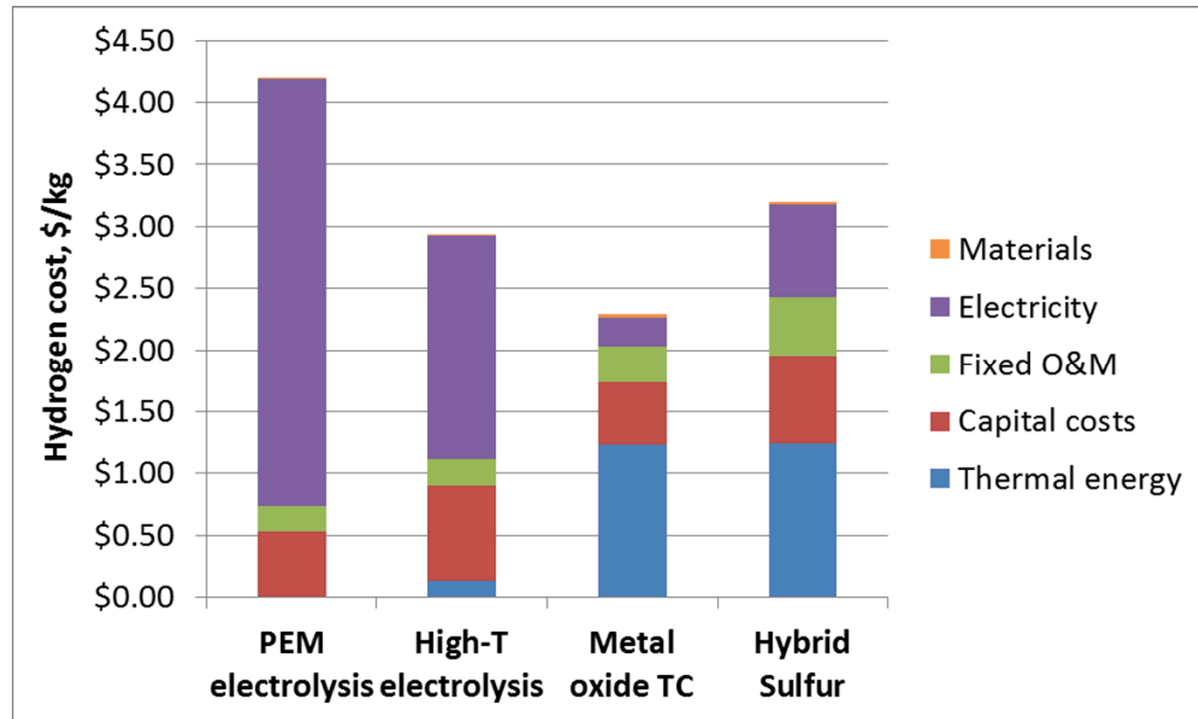


Thermal energy input varies by process

Hydrogen production costs

- Capital costs
- Fixed O&M costs
- Electricity cost
- Materials costs

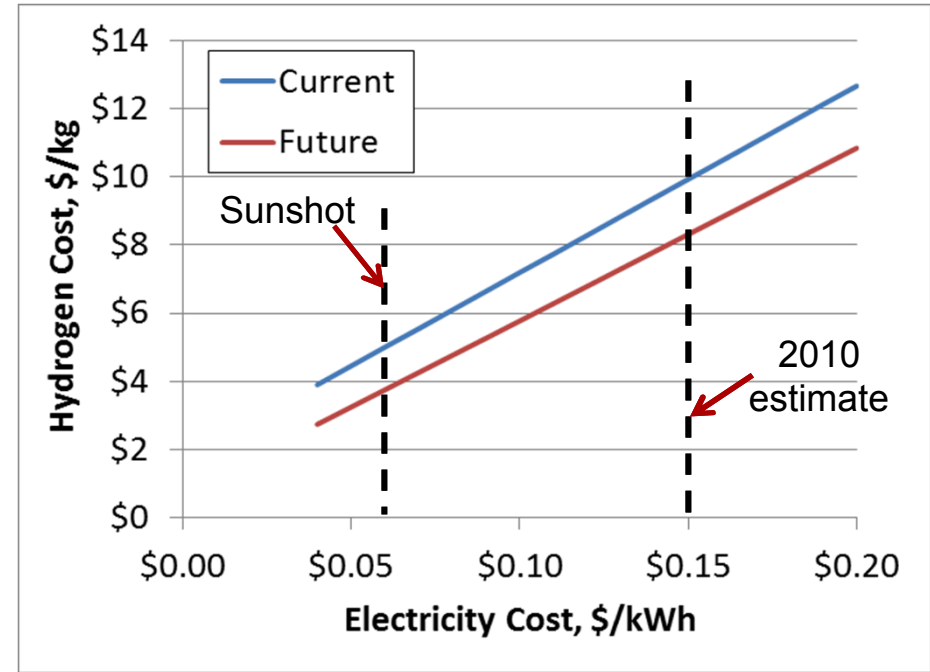
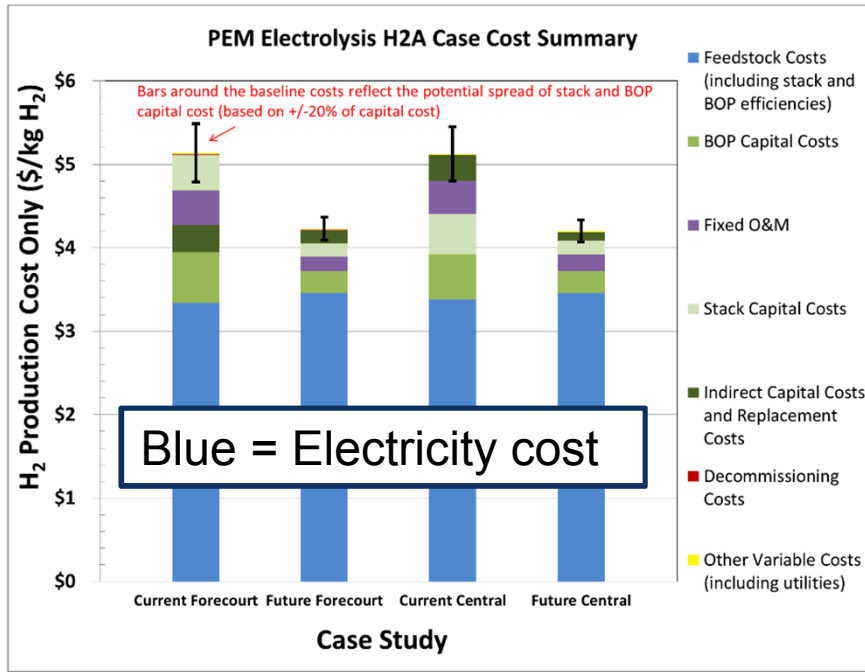
Costs extracted from H2A models



- High-T electrolysis leverages a relatively small amount of thermal energy to significantly increase efficiency of H₂ production
- Thermochemical metal oxide (TC) cycles convert larger amounts of thermal energy directly to chemical energy
 - Electricity is required to drive equipment, etc.

BASELINE CASE: PEM ELECTROLYSIS

PEM electrolysis case assumes no integration of H₂ production and electricity generation



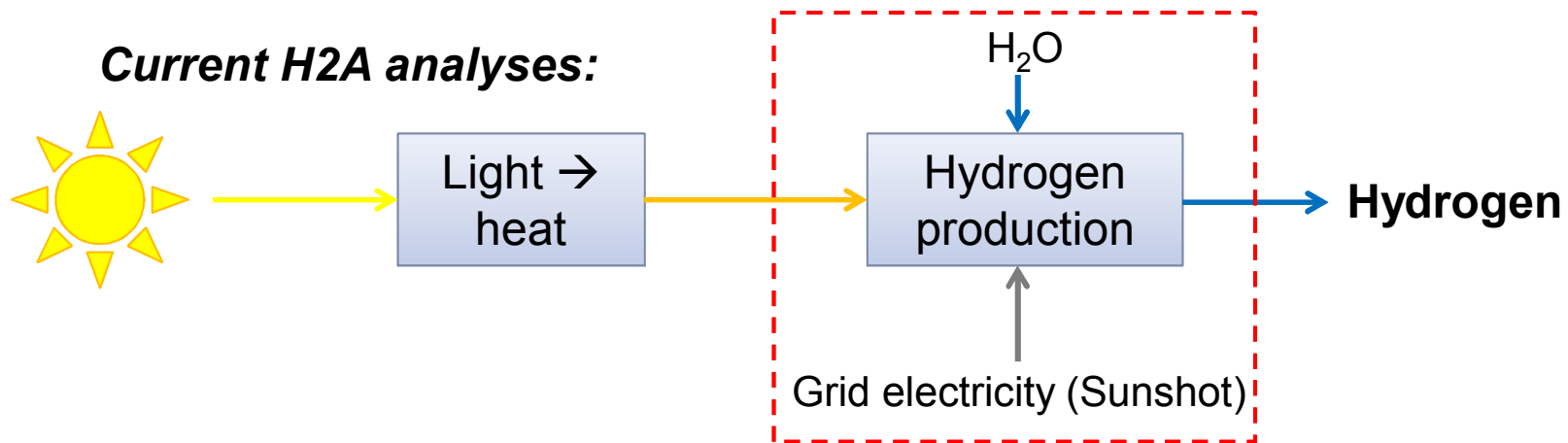
Source: James et al., *PEM Electrolysis H2A Production Case Study Documentation*, Grant DE-EE0006231, Arlington, VA, December 31, 2013.

Results from H2A model of Hydrogen Production from PEM Electrolysis .

- Electricity cost dominates H₂ production via PEM electrolysis
 - Using 2010 estimate of CSP costs (\$0.15/kWh), H₂ cost is \$8-10/kg
 - Using SunShot target (\$0.06/kWh), H₂ cost is \$3.75-\$5/kg
- One CSP tower provides enough electricity for H2A case (48,500 kg H₂/day)

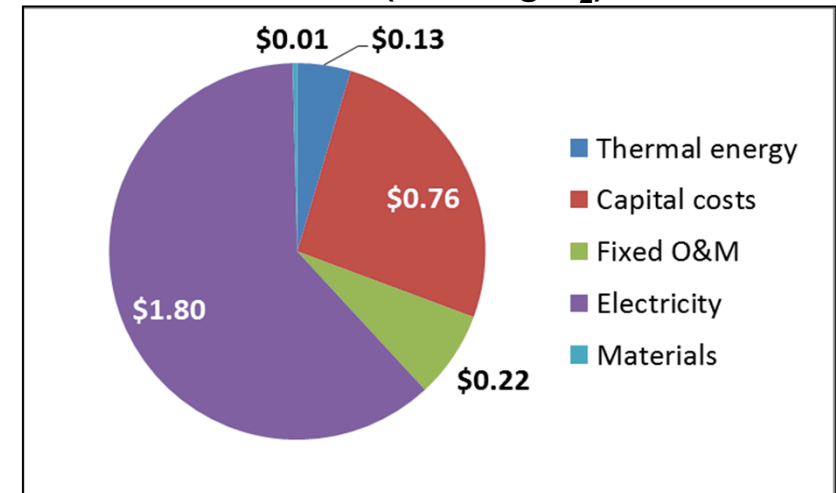
HIGH-T ELECTROLYSIS

High-T electrolysis uses thermal energy to increase efficiency



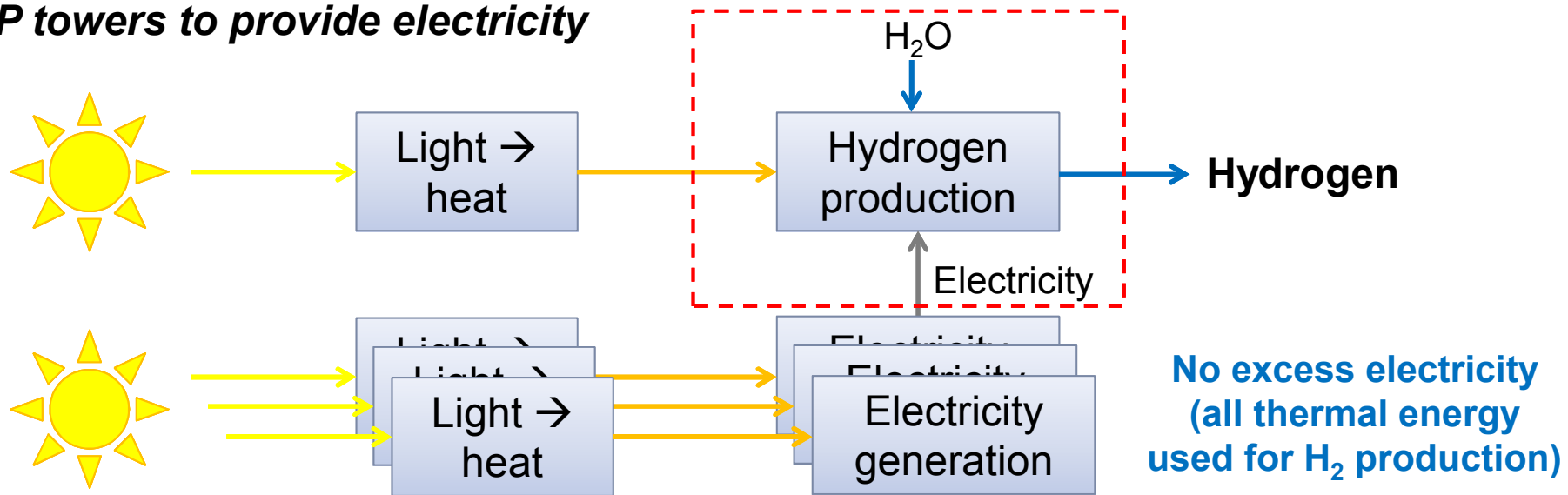
- H2A case is based on waste heat from a nuclear power plant → high throughput
- Thermal energy is used to raise the temperature of electrolysis
 - Heat input is relatively low: 6.8 kWh_T per kg H₂, versus electricity input of 33.2 kWh_e per kg H₂
 - H2A case assumes heat integration → no high-T “waste” heat

Breakdown of costs (\$2.93/kg H₂) for H2A case



High-T electrolysis integrated with CSP

Case 1: Single tower dedicated to providing thermal energy, multiple additional CSP towers to provide electricity



H₂A scenario for High-T Electrolysis is based on high throughput: 734,000 kg H₂/day

“Case 1” H₂ production rate is similar (~880,000 kg H₂/day)

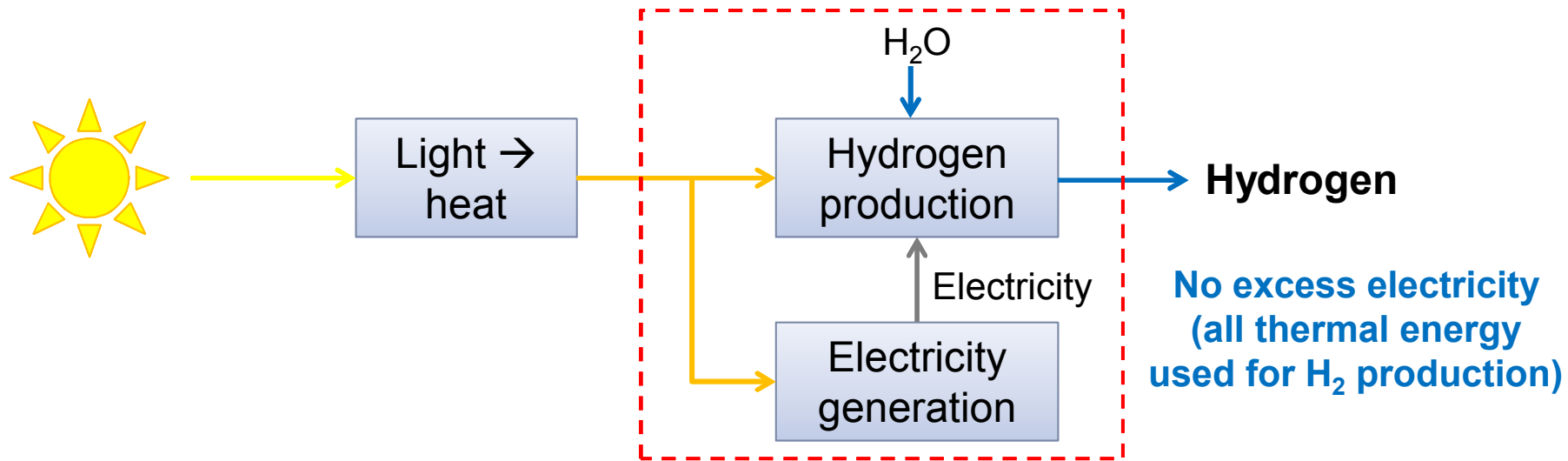
11 additional CSP towers would be necessary to supply necessary electricity

→ No excess electricity to sell to the grid

It is likely not feasible to co-locate and integrate CSP and H₂ production at this scale → Case 1 looks very similar to H₂A case

High-T electrolysis integrated with CSP

Case 2: Single tower dedicated to Hydrogen production



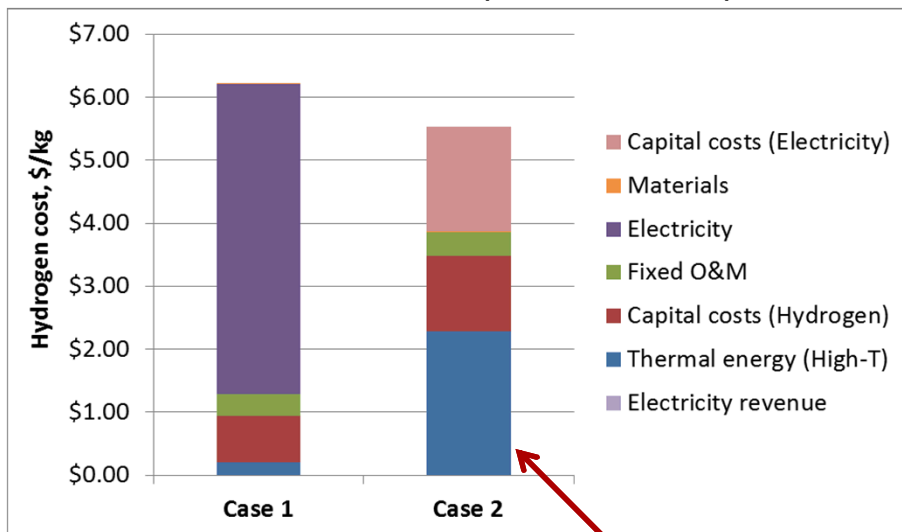
For Case 2, **9%** of thermal energy is used directly for H_2 production, **91%** of thermal energy is used for electricity generation

→ Total H_2 production is 80,000 kg/day (solar-to- H_2 efficiency, HHV basis = 20%)

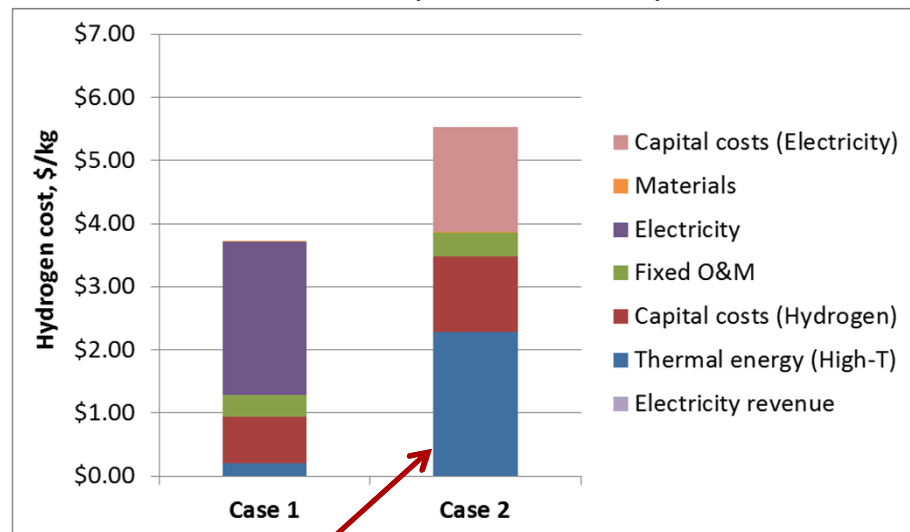
- H_2 production is $\sim 1/9^{\text{th}}$ that of H2A case → Capital costs per kg H_2 ↑
- Thermal energy for electricity gen is ≥ 650 C → Electricity generation efficiency ↑

High-T electrolysis integrated with CSP

California (\$0.13/kWh)



Arizona (\$0.07/kWh)

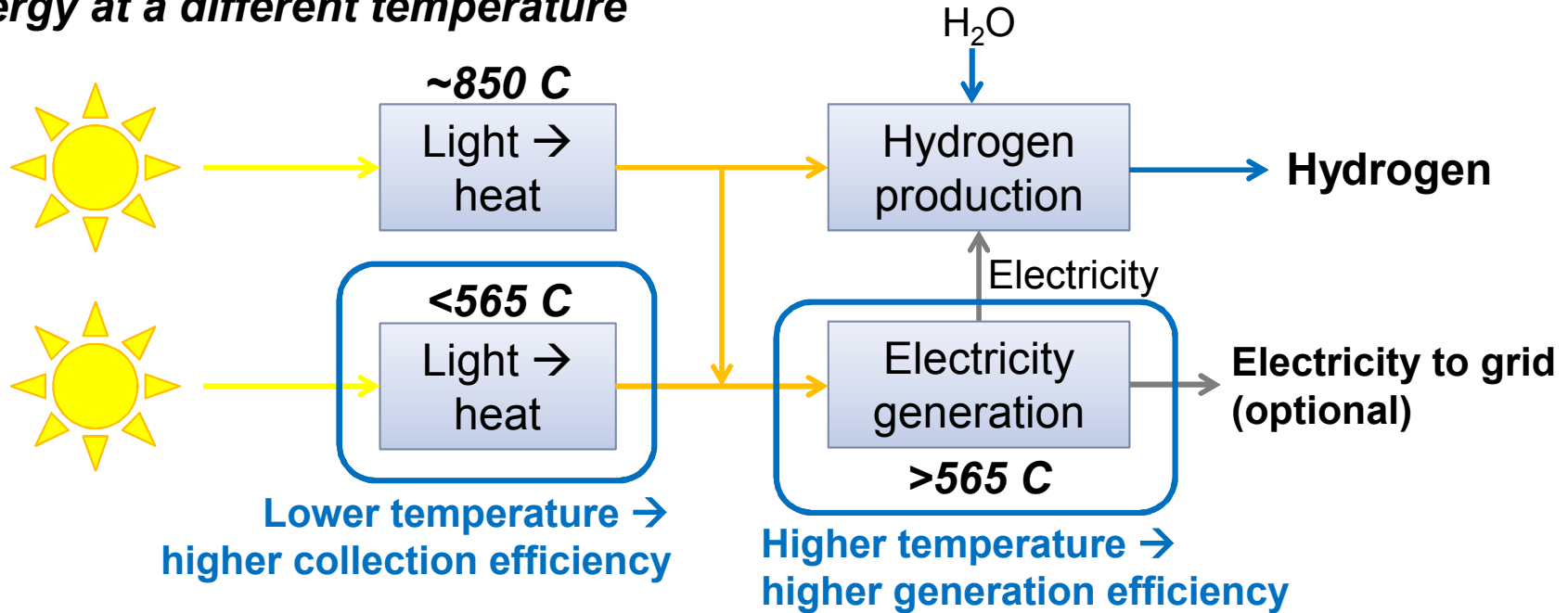


Most of thermal energy (91%) is used for electricity generation in Case 2

Attractiveness of Case 2 depends on cost of CSP relative to retail power

High-T electrolysis integrated with CSP

Case 3: Utilize two towers for hydrogen production, each providing thermal energy at a different temperature

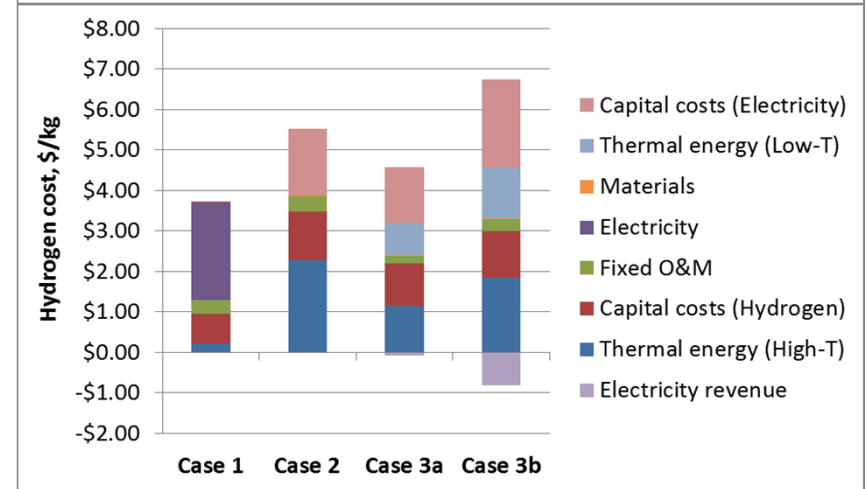
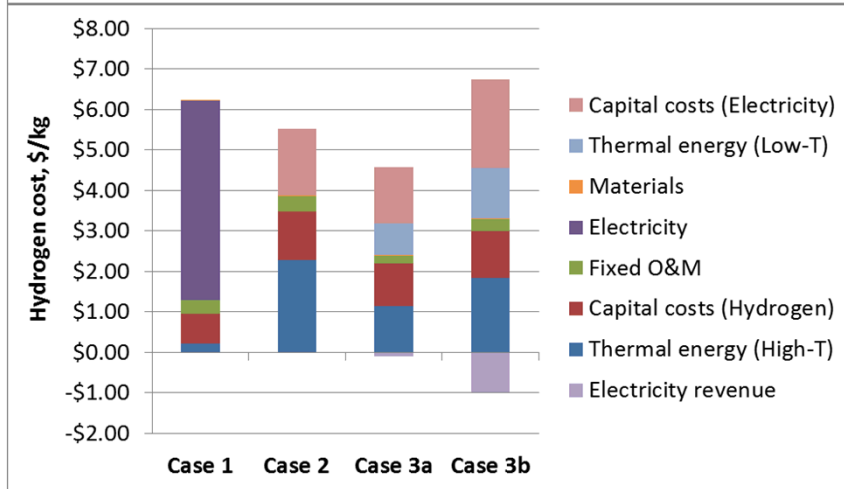
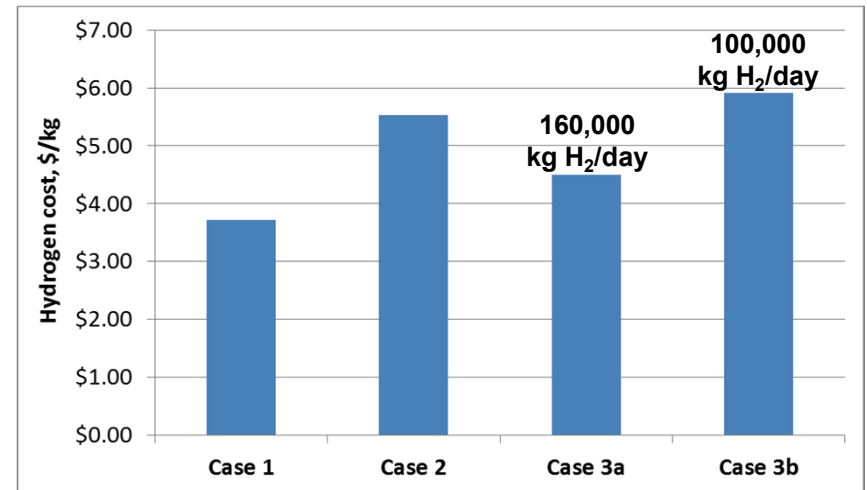
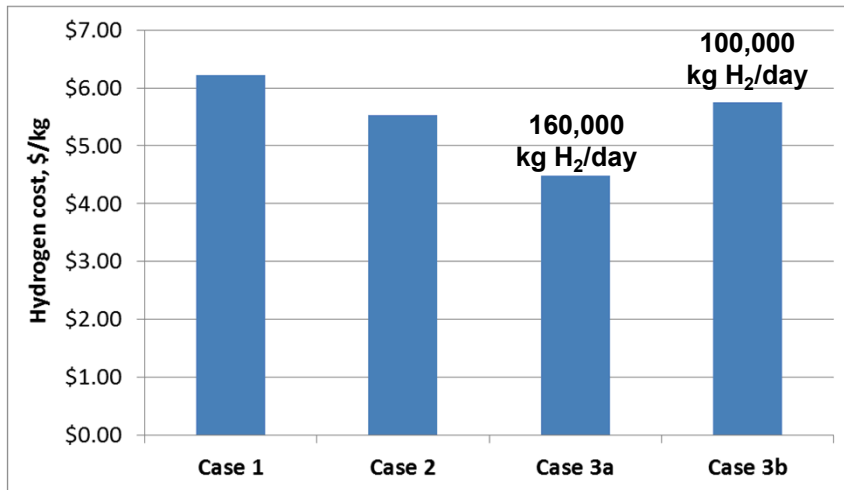


- Between 8% and 16% of thermal energy at 850C is used to raise electrolysis T
→ H₂ production between 80,000 kg/day and 160,000 kg/day
- Excess thermal energy from first tower and all thermal energy from the second tower is used for electricity generation
 - Raises temperature of electricity generation from 565 C to 600+ C
→ Electricity generation efficiency increases from **42%** to **48%**

High-T electrolysis integrated with CSP

California (\$0.13/kWh)

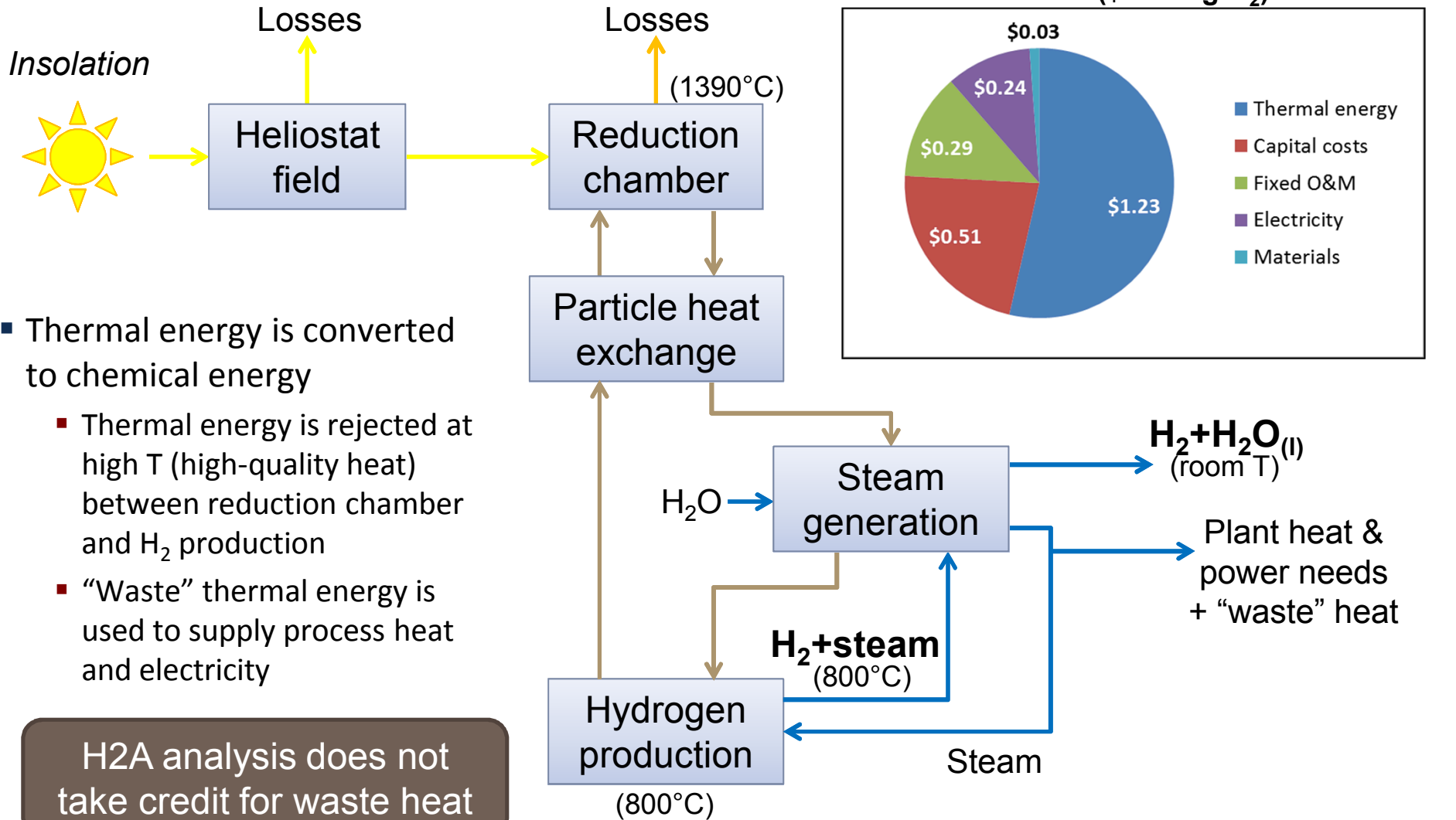
Arizona (\$0.07/kWh)



Under current assumptions, Case 3 with maximum H₂ production (160,000 kg H₂/day) is favored

METAL OXIDE THERMOCHEMICAL HYDROGEN PRODUCTION

Metal oxide TC cycle



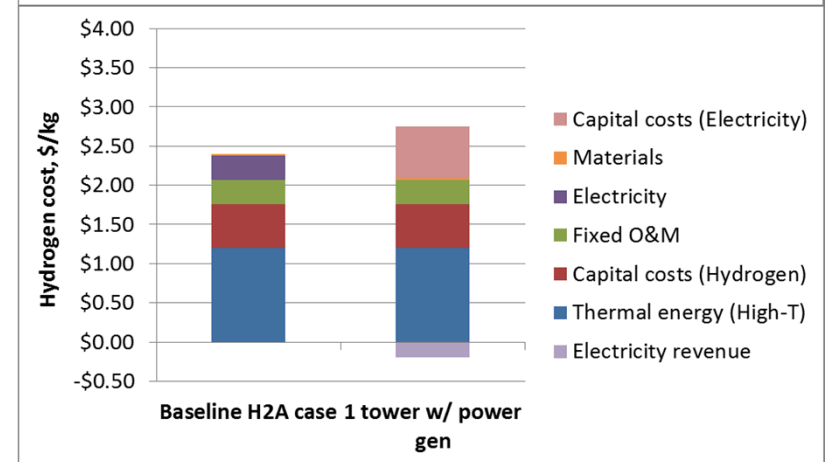
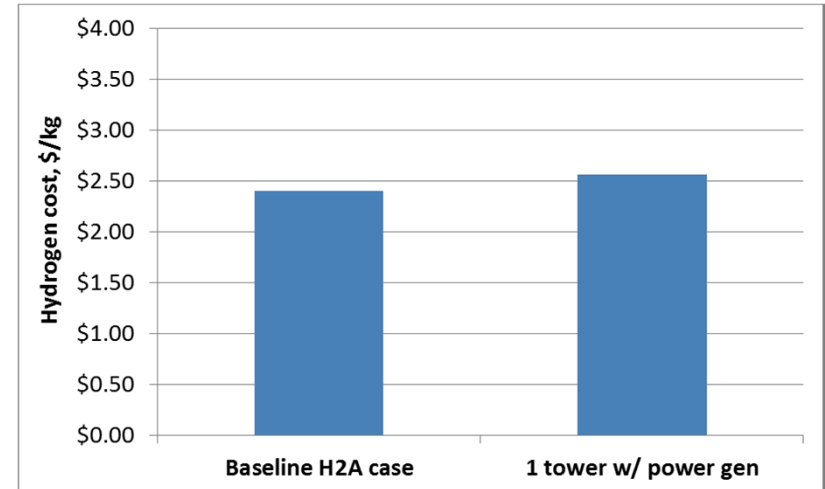
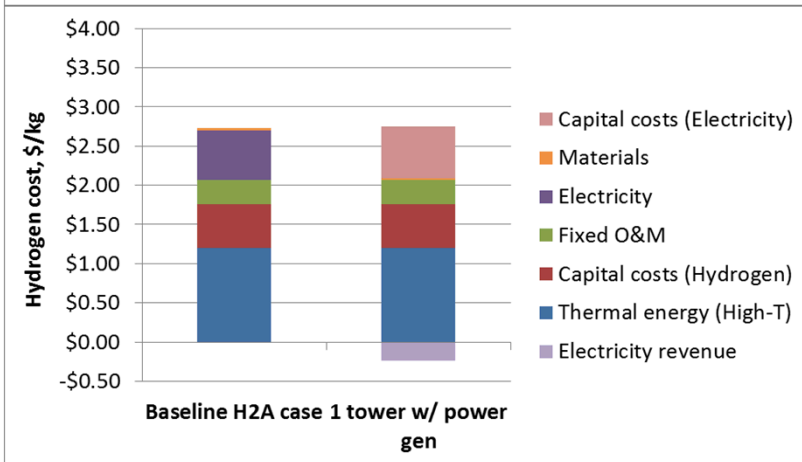
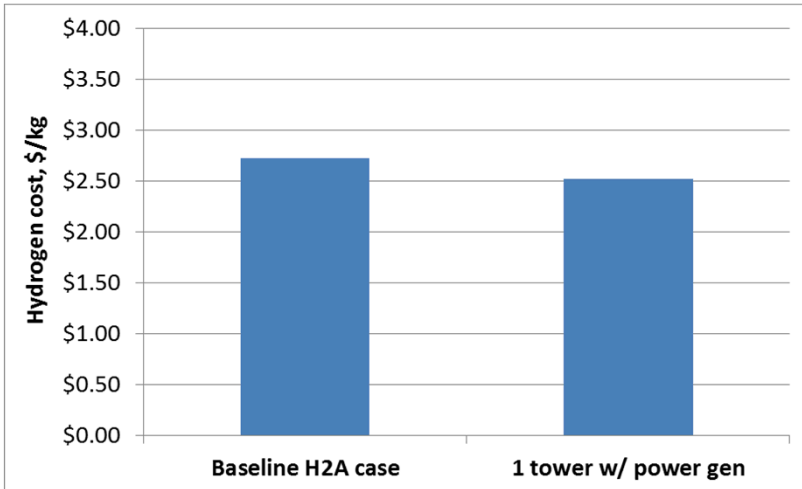
- Thermal energy is converted to chemical energy
 - Thermal energy is rejected at high T (high-quality heat) between reduction chamber and H₂ production
 - "Waste" thermal energy is used to supply process heat and electricity

H₂A analysis does not take credit for waste heat

Metal oxide TC cycle with electricity generation

California (\$0.13/kWh)

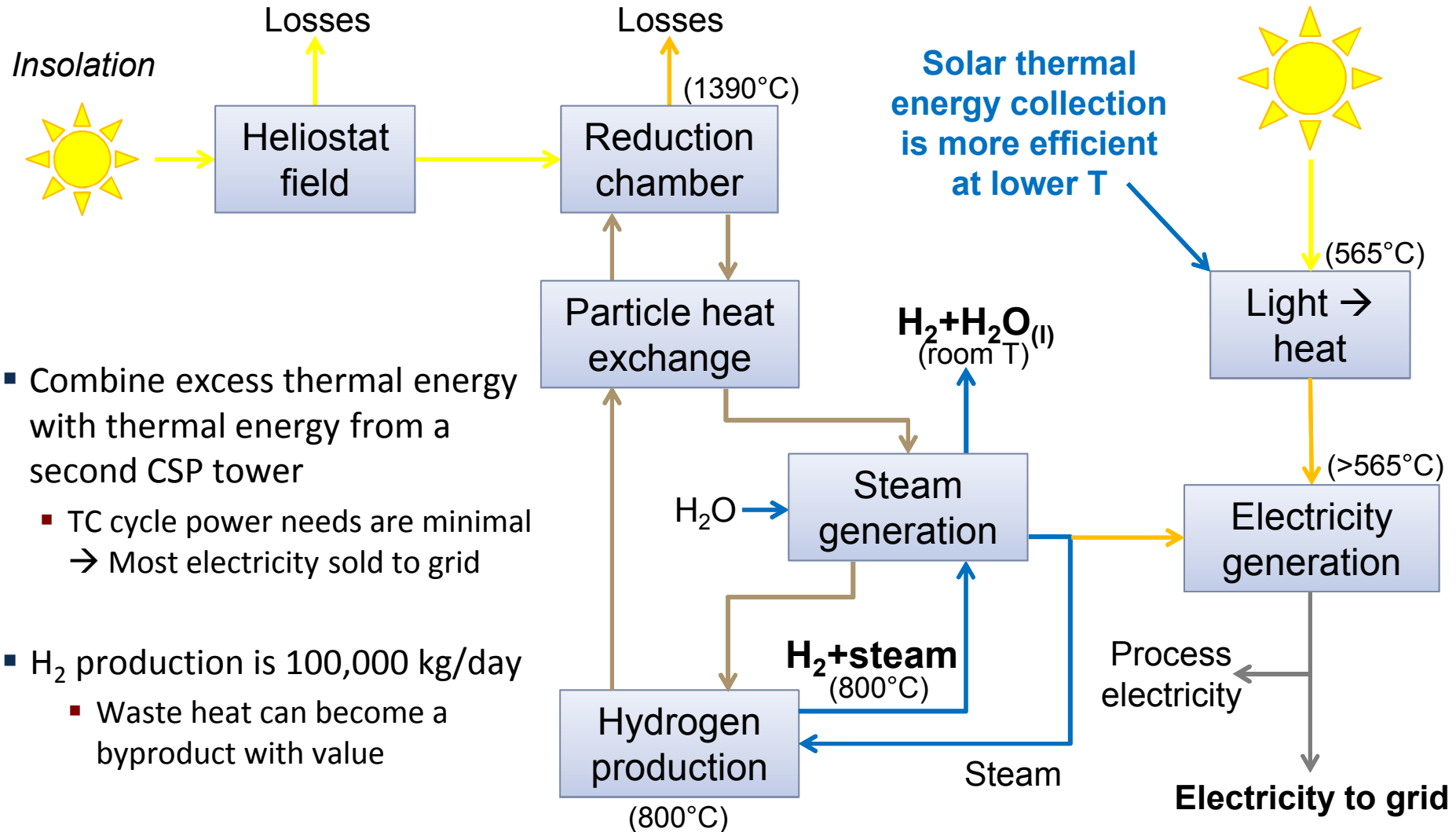
Arizona (\$0.07/kWh)



Electricity is a relatively small cost for metal oxide TC cycles

→ Generating electricity with waste heat does not significantly impact H₂ cost

Metal oxide TC cycle integrated with power tower electricity generation

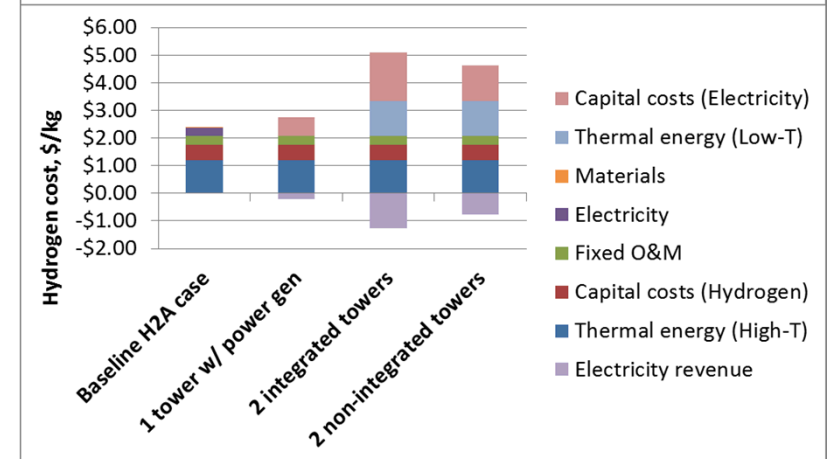
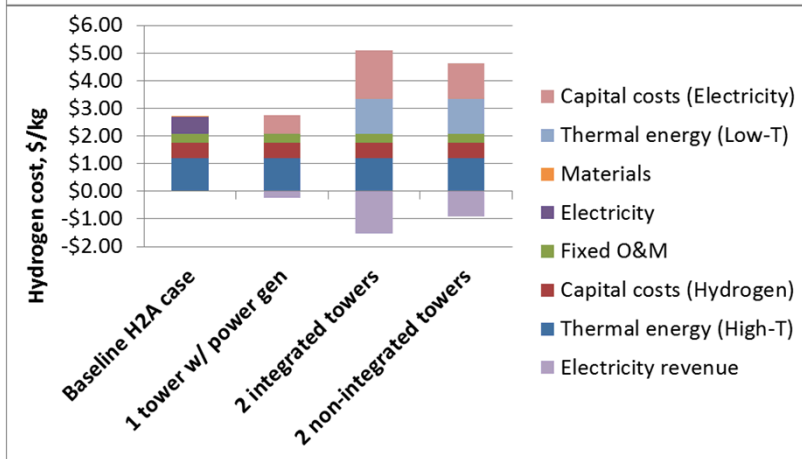
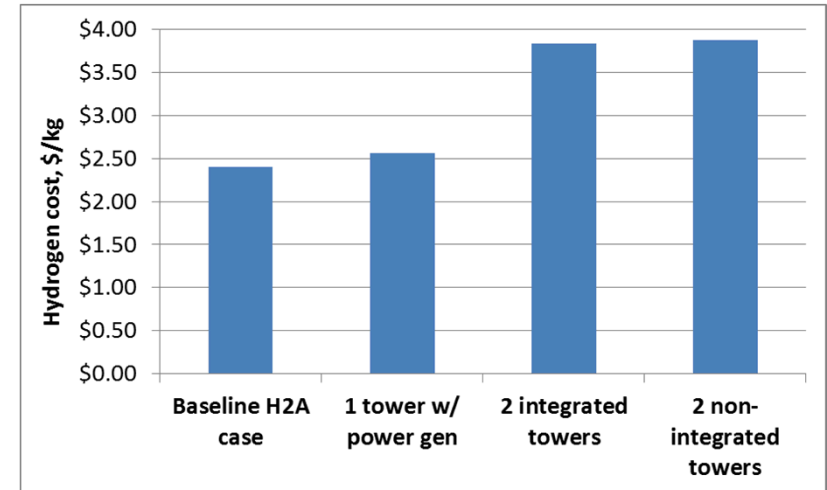
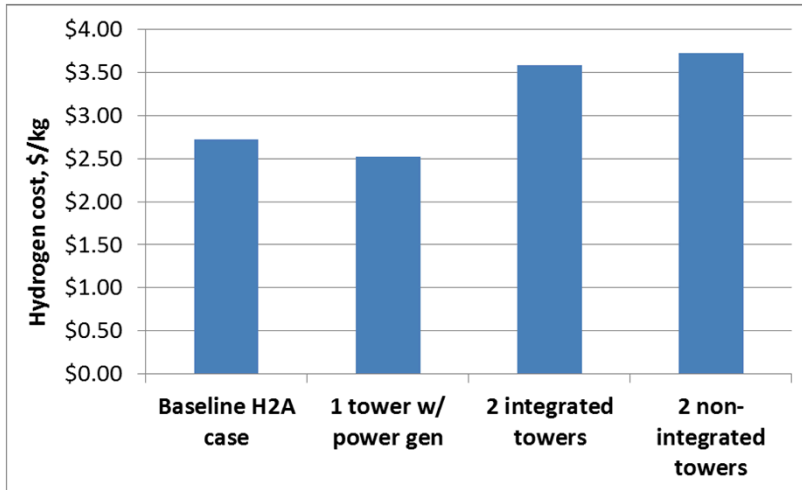


- Combine excess thermal energy with thermal energy from a second CSP tower
 - TC cycle power needs are minimal \rightarrow Most electricity sold to grid
- H_2 production is 100,000 kg/day
 - Waste heat can become a byproduct with value

Metal oxide TC cycle with electricity generation

California (\$0.13/kWh)

Arizona (\$0.07/kWh)

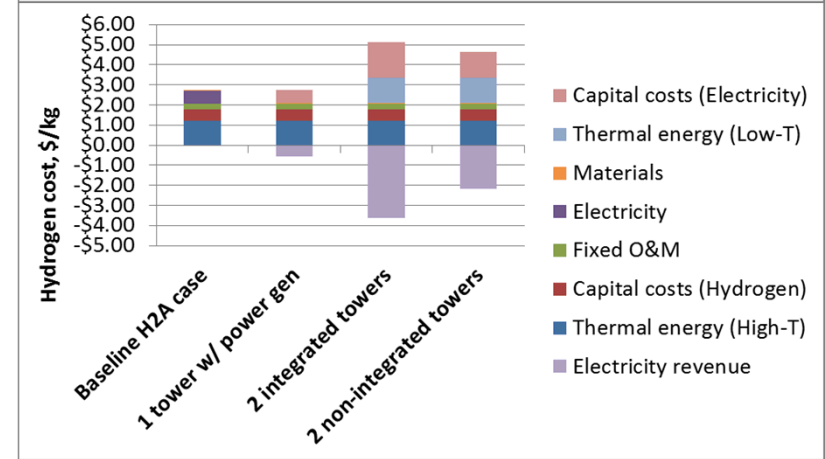
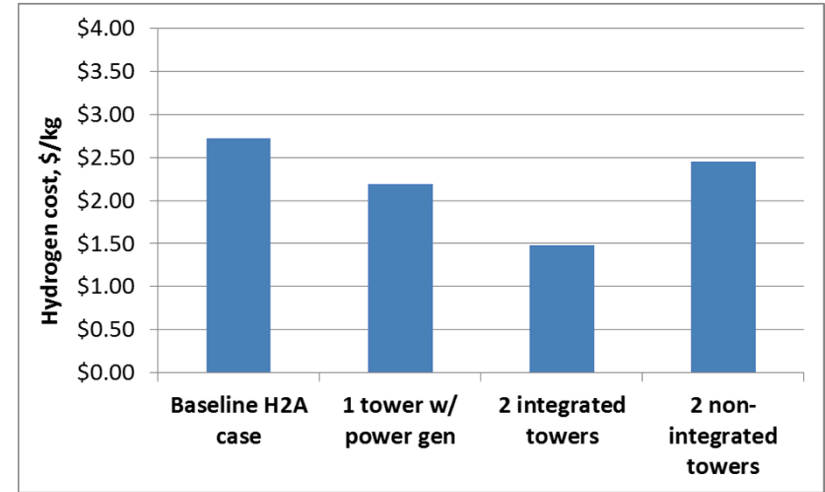
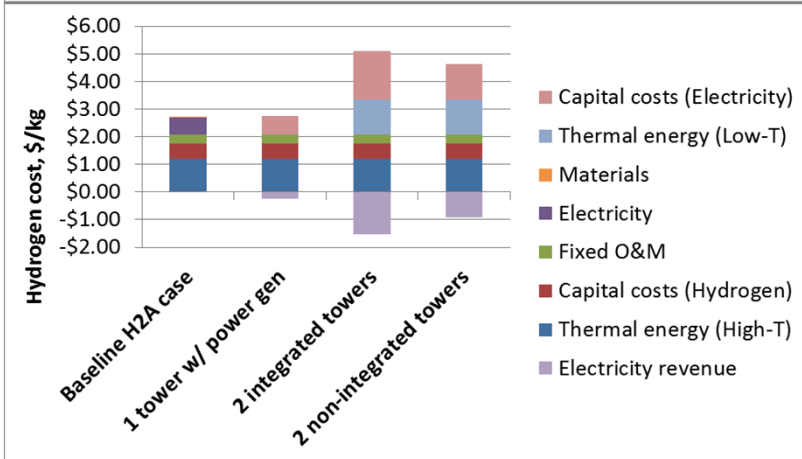
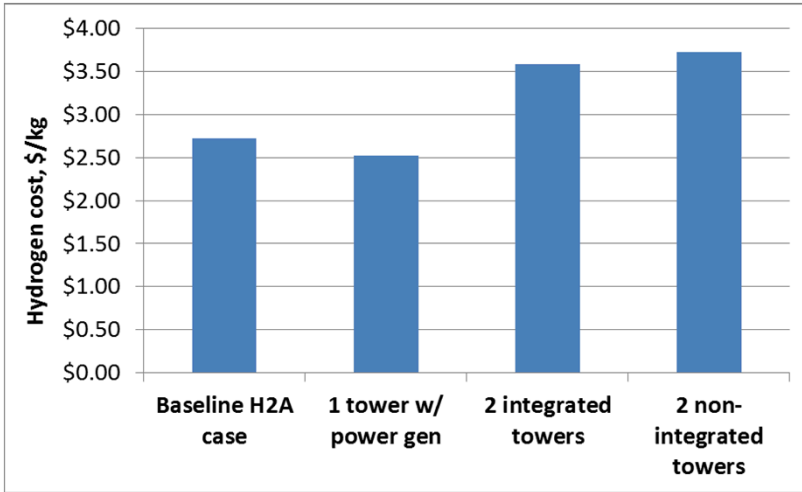


Assumptions regarding wholesale electricity price differentiate metal oxide TC cycle cases

Metal oxide TC cycle with electricity generation

\$0.13/kWh retail, \$0.04/kWh wholesale

\$0.13/kWh retail, \$0.10/kWh wholesale



Integrating two towers significantly reduces costs if CSP costs are below wholesale price

Conclusions and insights

- **Note:** CSP and solar H₂ technologies are at an early stage of development
 - Costs and performance are uncertain
 - Trends and insights are more important than the actual numbers
 - The goal of the current study is **not** to conduct optimizations

Conclusions and insights

- Electricity prices have a significant impact on the analysis results
 - From the perspective of H₂ production, CSP-H₂ integration is favored when CSP price is lower than electricity price
- For High-T electrolysis, relatively small amounts of high-quality heat are required compared to electricity needs
 - It will likely not be feasible to match the scale of nuclear-based H₂ production with co-located CSP generation
 - No high-T waste heat is available from either CSP or H₂ production
 - High-T heat is diverted to either CSP or raising temperature of electrolysis
 - Economics will favor production of a single product
 - Integration of multiple towers reduces costs via economies of scale and more efficient collection of thermal energy
 - **CSP costs vs retail electricity price** determines whether heat should be used for electricity or heating electrolyzer

Conclusions and insights

- For metal oxide TC cycles, high-quality “waste” heat is available in larger quantities than is needed for electricity generation
 - Integration with CSP is attractive
 - Waste heat represents a valuable potential feedstock for CSP
 - High-T: Increases efficiency of electricity generation from 41% to 48%
 - Merits of full integration of CSP and H₂ production depend on **wholesale electricity price**
 - Future metal oxide TC cycles assume no heating of inert material, 90% recuperation of high-T heat
 - Current metal oxide TC cycles will generate significantly more waste heat

Draft report outline

- Introduction
 - Background and project objectives
 - Analysis scope
- Analysis approach
 - Background
 - CSP (Power tower) overview
 - Solar H₂ production overview
 - Scenarios for analysis
 - Scenario 1: PEM water electrolysis using grid-delivered CSP (Baseline scenario)
 - Scenario 2: High-T electrolysis integrated with CSP
 - Scenario 3: High-T thermochemical H₂ cycle integrated with CSP
 - Modeling approach
- Results & Discussion
 - Solar thermal energy as a feedstock
 - General considerations for integrating CSP and H₂ production
 - Performance estimates for integrated CSP and H₂ production scenarios
 - PEM electrolysis (Baseline scenario)
 - High-T electrolysis
 - Metal oxide TC cycles
 - The impact of uncertainties in system cost and performance
- Conclusions
 - Potential areas for collaboration/synergies between CSP and H₂ production

Discussion

- Assumptions
 - Ownership model
 - In the case of two integrated towers, assume that both towers are owned by the same entity
 - Sell electricity at wholesale price, account for revenue in H₂ cost
 - Electricity prices
 - CA: \$0.134/kWh retail (industrial), \$0.042/kWh wholesale
 - AZ: \$0.066/kWh retail (industrial), \$0.035/kWh wholesale
 - Equipment costs
 - For H₂ production: Costs from “Future” H2A worksheets
 - For CSP: Costs to reach SunShot target
- Is the story complete?
 - What conclusions or insights are most relevant for FCTO?