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Potential Strategies for Integrating Solar Hydrogen Production and Concentrating Solar Power: A Systems Analysis

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Sandia National Laboratories

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Introduction
  - Background
  - Modeling approach
  - Key assumptions
  - Concentrating solar power (CSP) overview
  - General comments on CSP-H_2 integration
- CSP-H_2 integration scenarios
- Conclusions and insights

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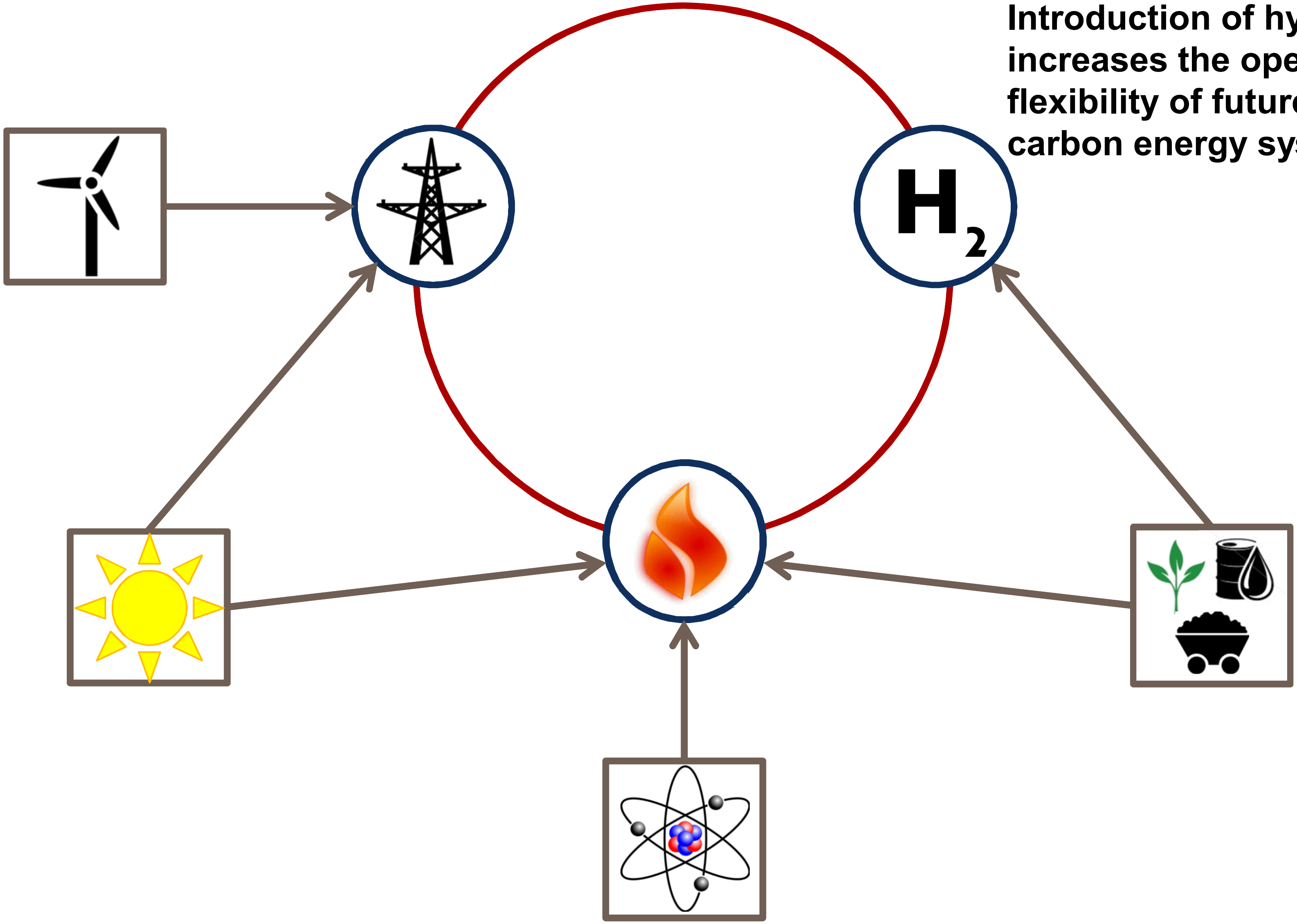
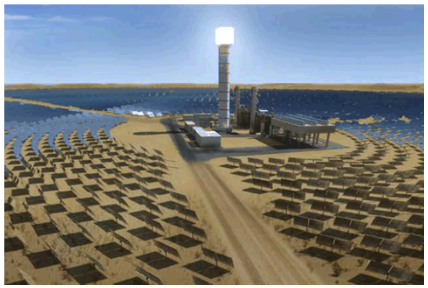
Hydrogen, heat, and electricity provide links between energy sources



Introduction of hydrogen increases the operational flexibility of future low carbon energy systems

Hydrogen, heat, and electricity provide links between energy sources



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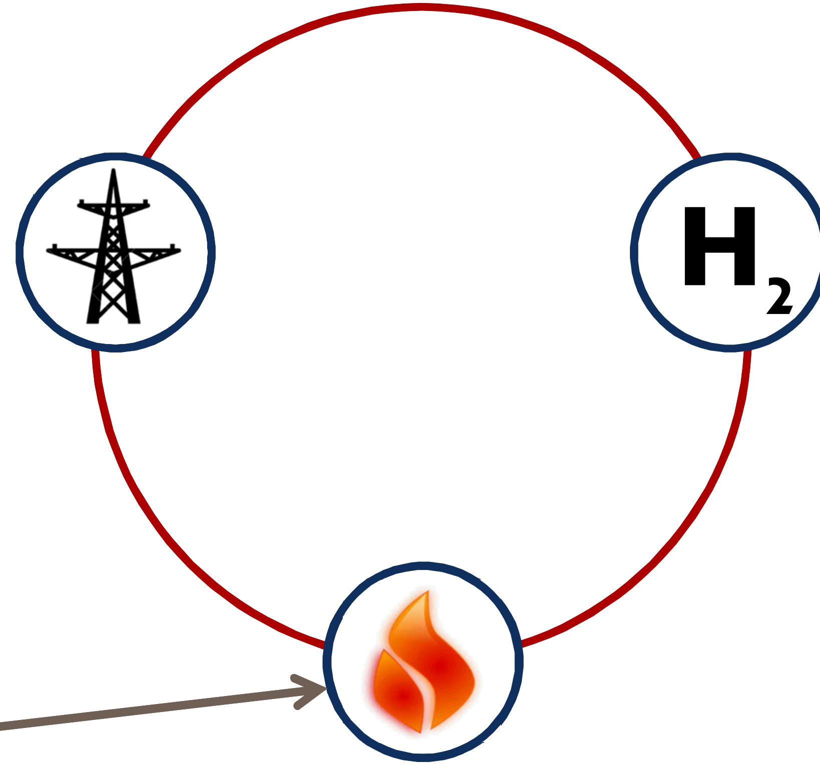

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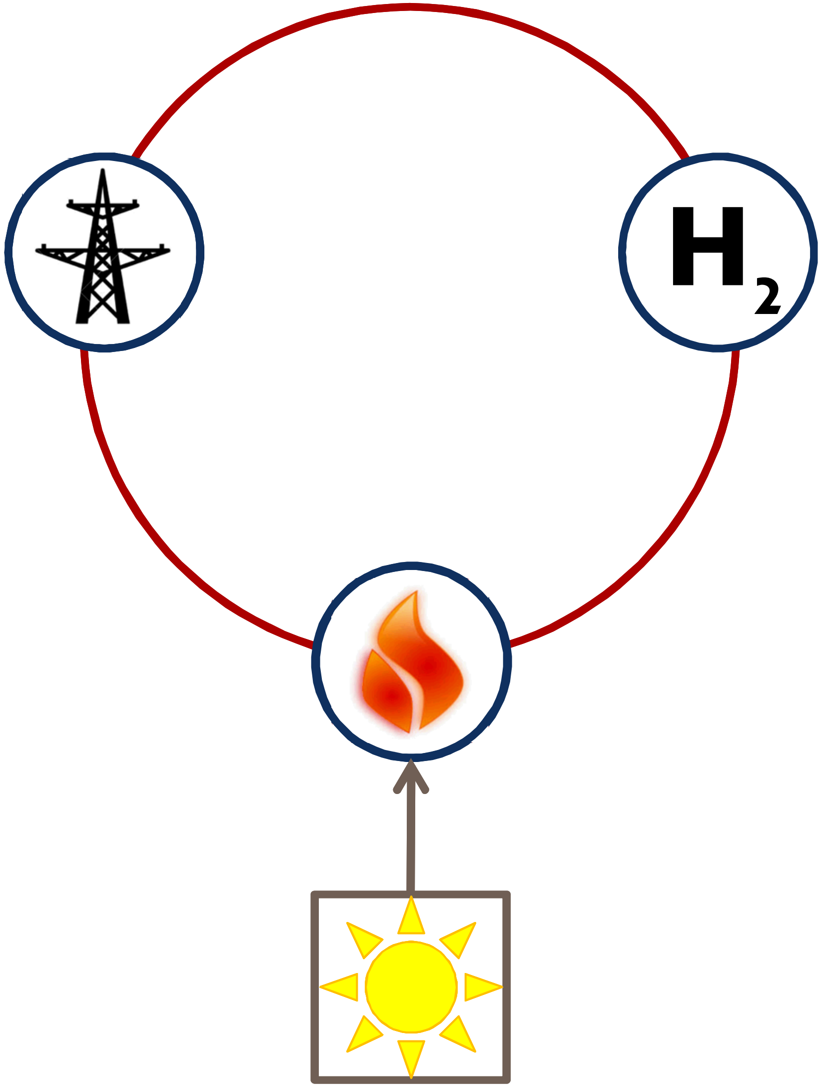
Focus of the current analysis: ***Hydrogen*** and ***electricity*** production from solar energy in the form of ***heat***

Hydrogen, heat, and electricity provide links between energy sources



Analysis Goal: Explore pathways for integrating concentrating solar power (CSP) and solar hydrogen production

→ **Do synergies exist that could reduce costs?**

Analysis Scope: Process-level integration of CSP and H_2 production

- No consideration of H_2 for energy storage
- No transportation/geographical considerations (e.g., benefits of co-locating H_2 production near H_2 users)

Modeling approach leverages previous analyses of CSP and H_2 production

CSP

Published reports / models developed at Sandia

- Power conversion calculations and reliability analysis
- Capital and O&M cost estimates

→ Levelized cost of electricity (LCOE)

- Cost reduction / performance targets

H_2 Production

DOE H_2 production models

- Discounted cash flow analysis based on conversion efficiency and capital, O&M, and materials costs
- Output is cost of H_2 per kg

Key relationships were extracted and represented in a simplified Excel-based model

Objectives:

- Identify important performance drivers and ***fundamental conditions*** that favor CSP-H_2 integration (***NOT*** process optimization)
- Understand ***key uncertainties*** and ensure robustness of conclusions

Assumptions: Process performance and costs

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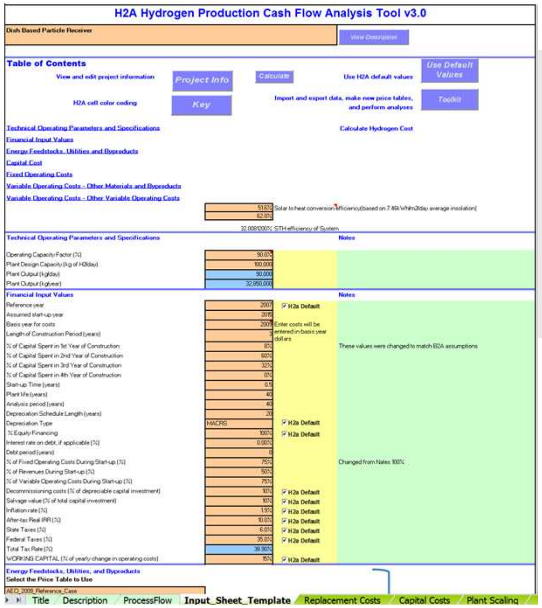
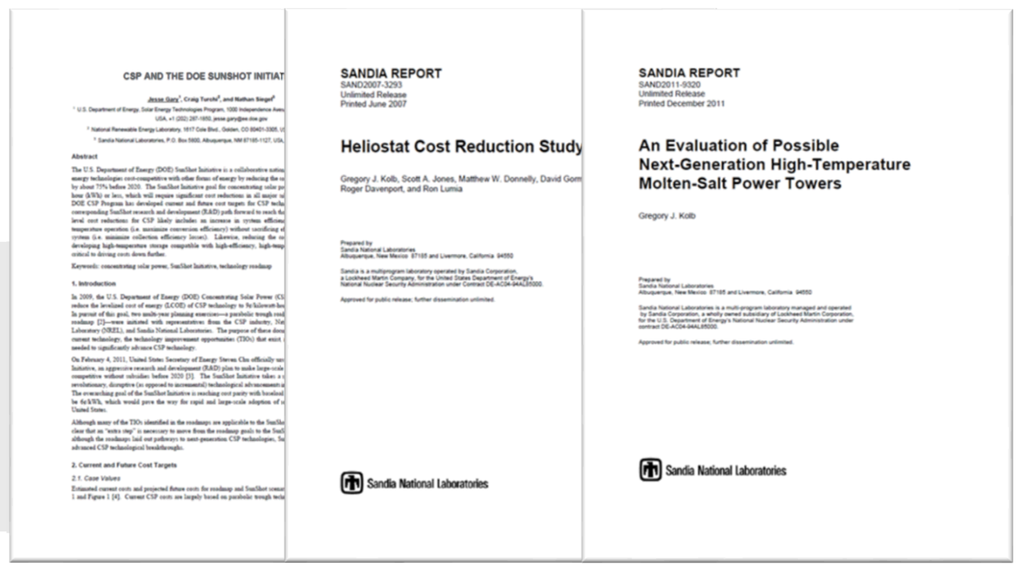


H_2 Production: Process configurations and costs taken directly from DOE H_2 Analysis (H2A) models
→ ***"Future Central Hydrogen Production"*** (start-up year: 2025-2030)



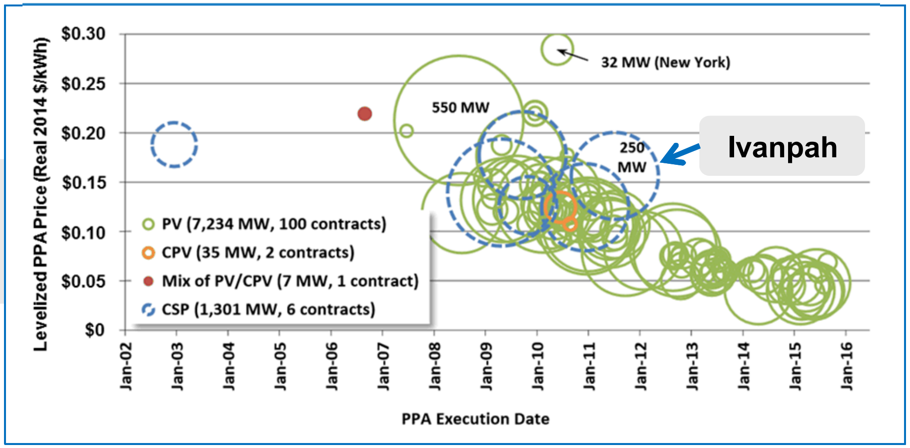
CSP: Process configurations and costs taken directly from DOE and National Laboratory reports
→ ***SunShot*** target costs (2020)

For both H_2 production and CSP, assumptions are based on ***future systems***

Assumptions: Future electricity prices

- Current electricity prices[1]:
  - CA: \$0.13/kWh retail (industrial), ~\$0.04/kWh wholesale
  - AZ: \$0.07/kWh retail (industrial), ~\$0.03/kWh wholesale
- Recent analysis shows solar Power Purchase Agreements (PPA) reaching grid parity (after incentives)

Source: Bolinger & Seel, "Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States," LBNL-1000917, September 2015

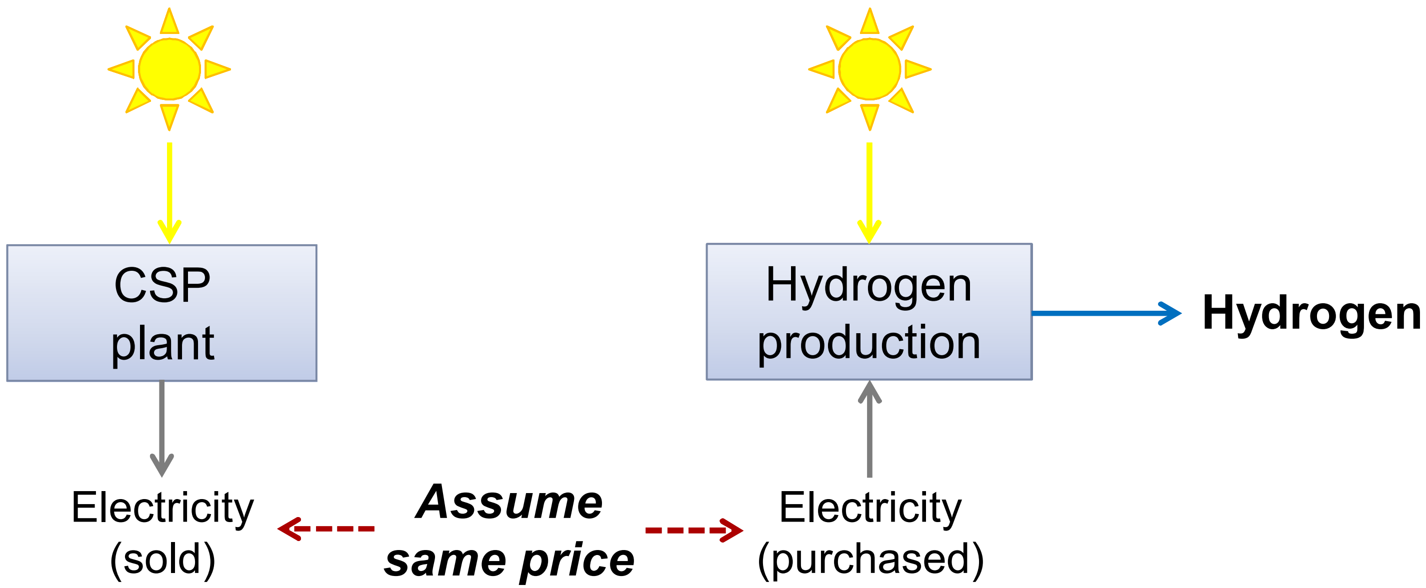


- However, several factors could lead to higher electricity prices
  - Potential increases in natural gas prices (share of electricity generation is rising)
  - Renewables Portfolio Standards (RPS), Cap and Trade, US EPA's Clean Power Plan, etc. → Could increase the price of renewable power
  - As penetration of wind and PV ↑, storage capability of CSP could command a premium

[1]Source: EIA

Assumptions: Future electricity prices

- Future electricity prices (2020-2030) are highly uncertain → ***Parameterize***

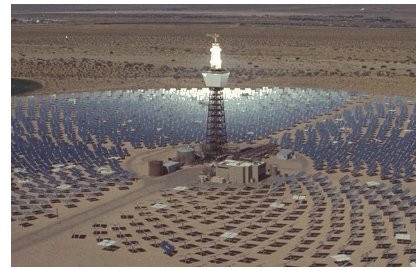


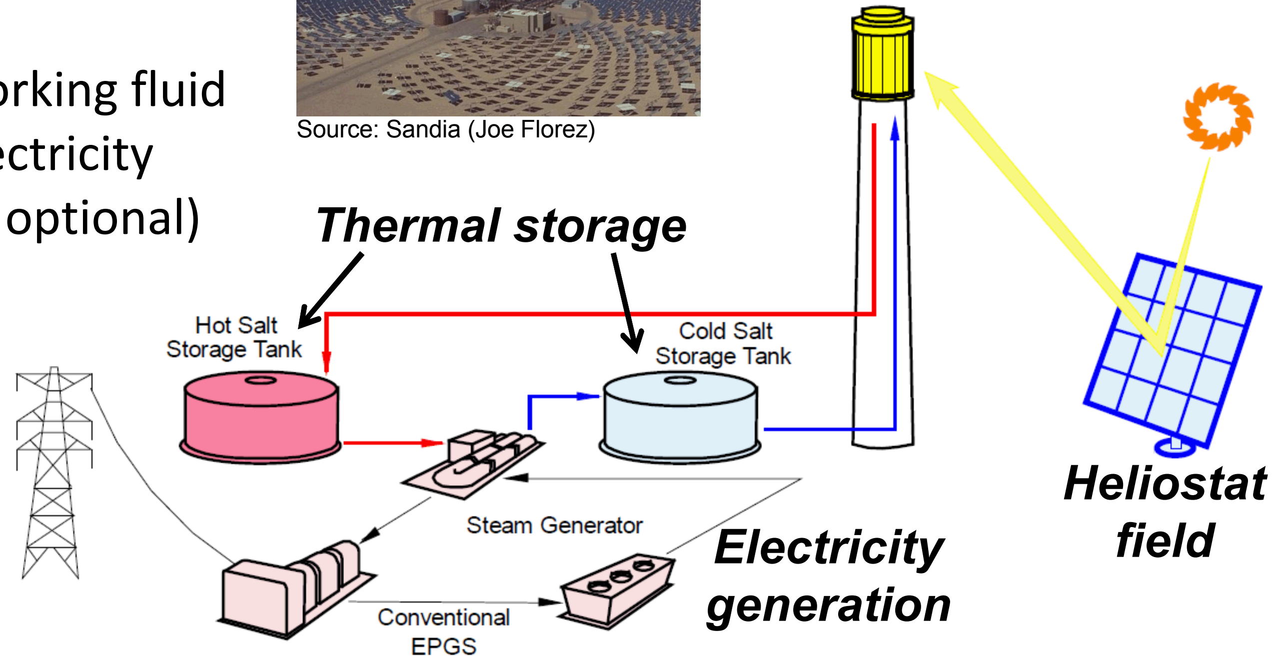
- Assume H_2 plant could purchase electricity at same price that a CSP plant could sell electricity
- Assume CSP and H_2 production facilities owned by same entity
  - H_2 is the primary product → account for electricity revenue in H_2 cost

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

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%

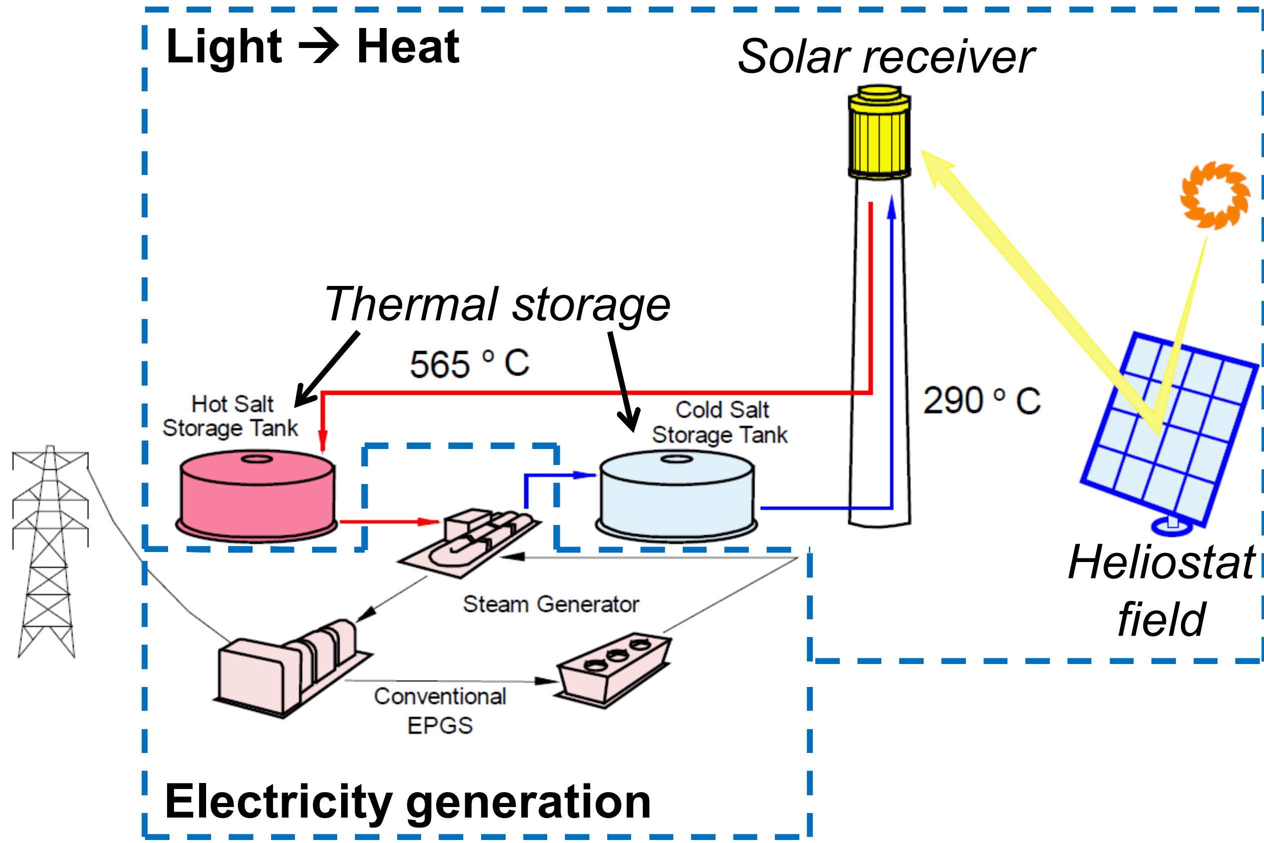

Source: Sandia (Joe Florez)

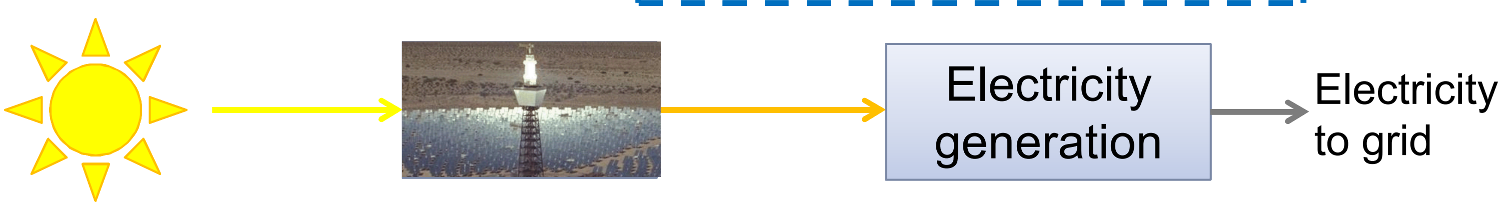


Baseline CSP plant: Power Tower configuration with molten salt thermal storage and subcritical Rankine cycle electricity generation
→ 2010 Sandia estimate: \$0.15/kWh; SunShot goal: \$0.06/kWh

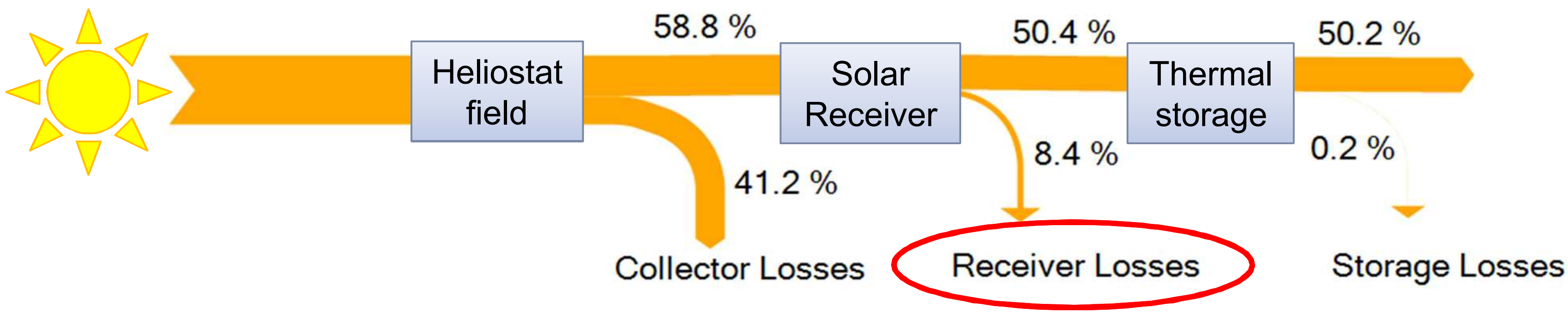
Define major CSP units for analysis

- Collection of light and conversion to thermal energy (Light → Heat)
  - Heliostat field
  - Solar receiver
  - Thermal storage
- Electricity generation
  - Steam generator
  - Turbine
  - Cooling towers





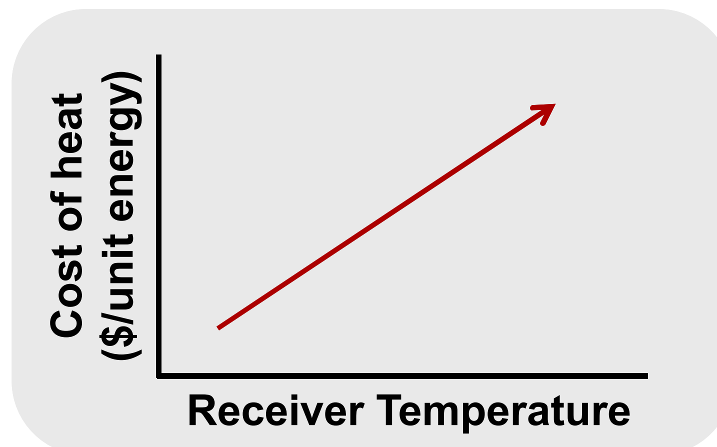
Heat can be treated as a "feedstock"



Receiver losses ↑ as T ↑

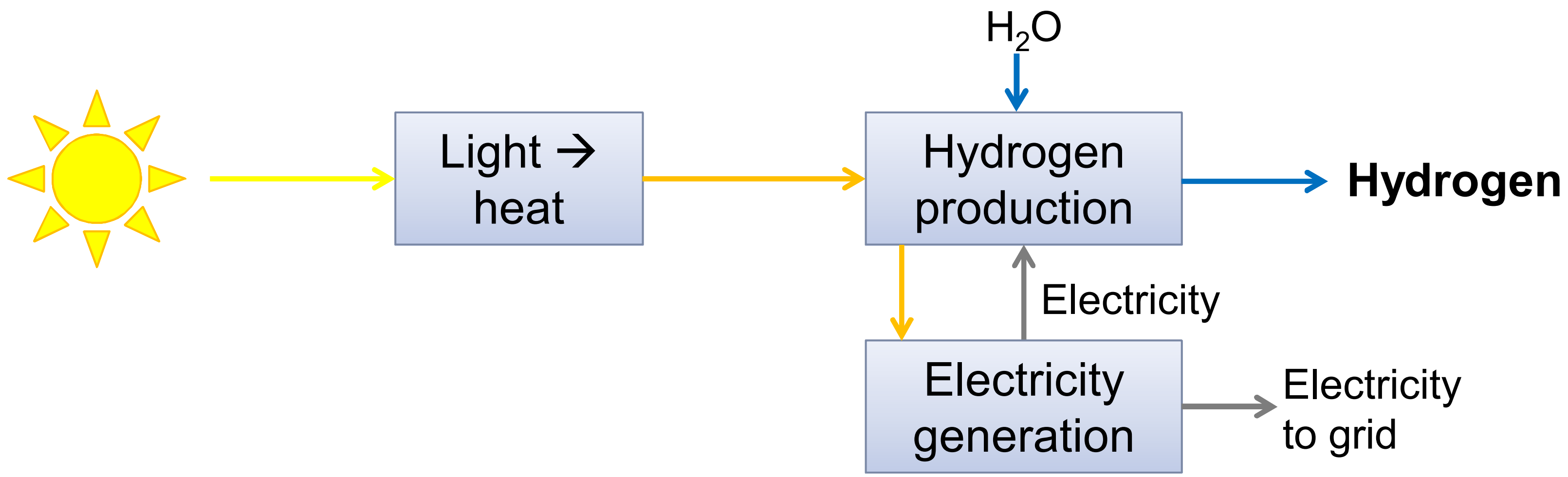
Heat "quality" is defined by:
- Temperature
- Availability (storage)

Solar thermal energy "feedstock" is a major cost;
Cost rises with temperature



However, higher T allows ***more efficient*** production of electricity or H_2

Goal: Investigate opportunities for integrating H_2 production and CSP processes



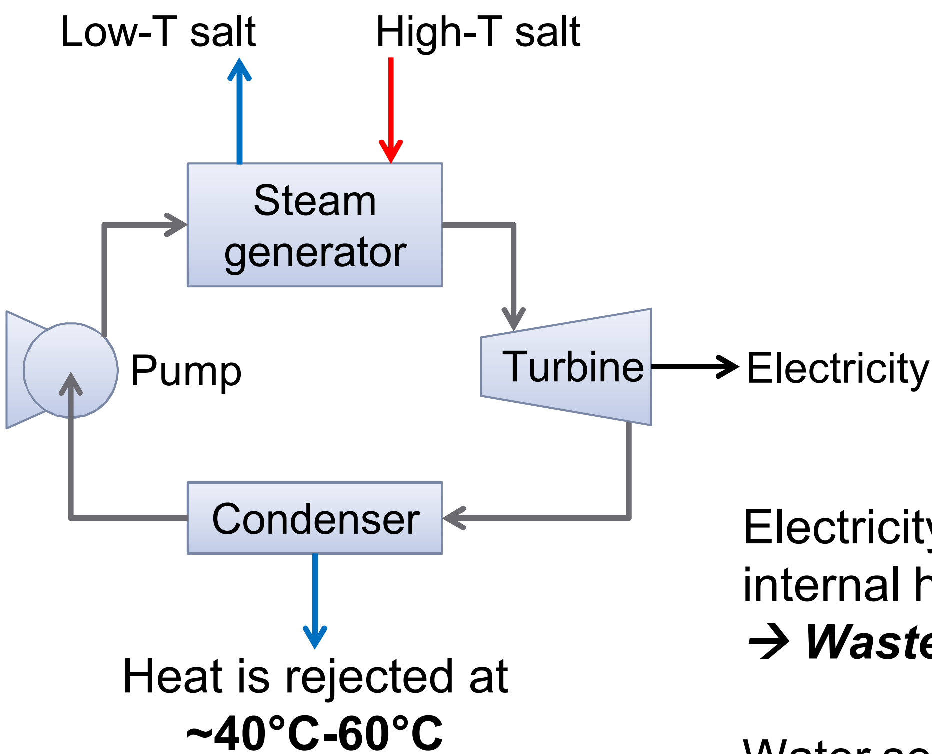
H2A analyses assume ***purchase*** of grid electricity
→ Current analysis considers ***co-production*** of electricity (CSP)

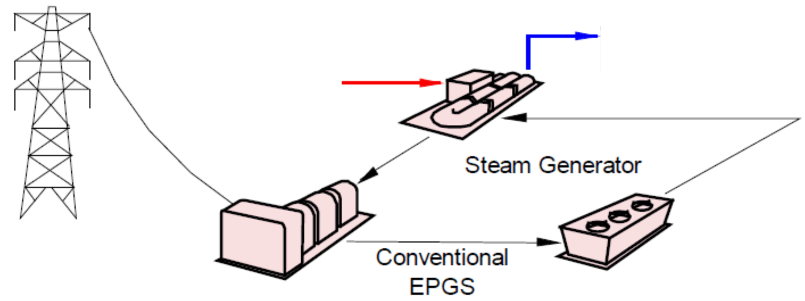
Key question to ask for each process: Are there potential synergies between the processes which would favor co-location of CSP and H_2 production?

- Waste heat streams
- Byproducts → Feedstocks

Thermal energy is a major cost → Focus on heat streams for CSP-H_2 integration

CSP yields few byproducts





Electricity generation cycles feature efficient internal heat integration
→ ***Waste heat exiting system is of low quality***

Water serves as working fluid in closed cycles
→ ***No significant material waste streams***

Look to H_2 production processes for integration opportunities

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Three scenarios 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

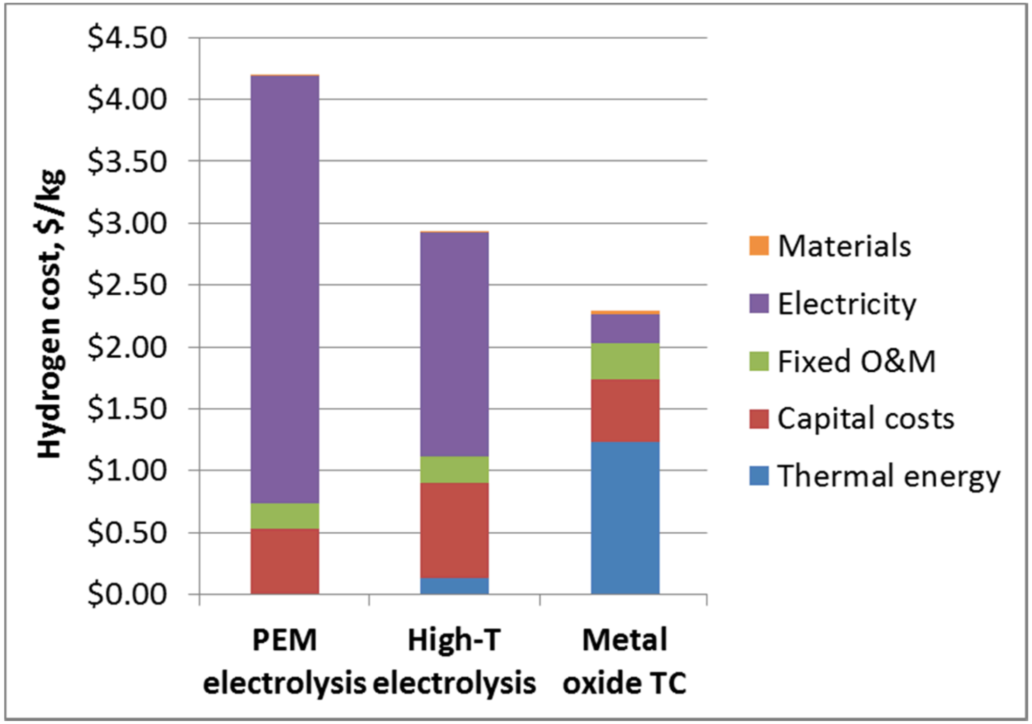
3. High temperature (1380 C) metal oxide thermochemical (TC) H_2 production integrated with a CSP plant

Thermal energy input varies by process

Hydrogen production costs

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

Data sources:
H2A models of H_2 production



- High-T electrolysis leverages a relatively small amount of thermal energy to significantly increase efficiency of H_2 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 H_2 production and electricity generation

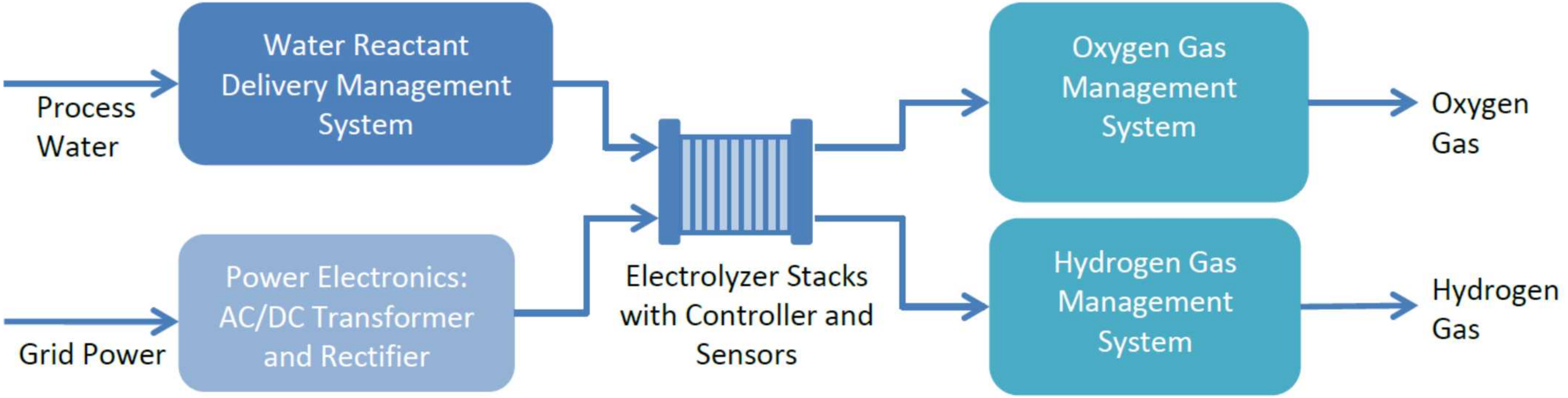
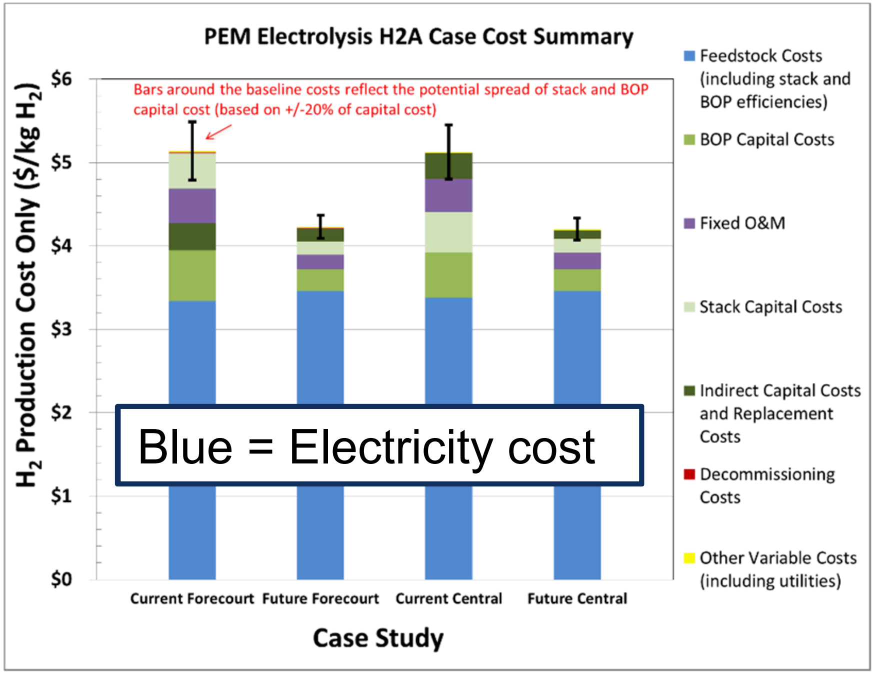


Image Source: James et al., *PEM Electrolysis H2A Production Case Study Documentation*, Grant DE-EE0006231, Arlington, VA, December 31, 2013.

- Main inputs are water and electricity → ***No heat inputs***
- Electrolyzer stack, power electronics, and H_2 gas management system account for most of capital costs (~70%)

Electricity costs dominate for PEM electrolysis



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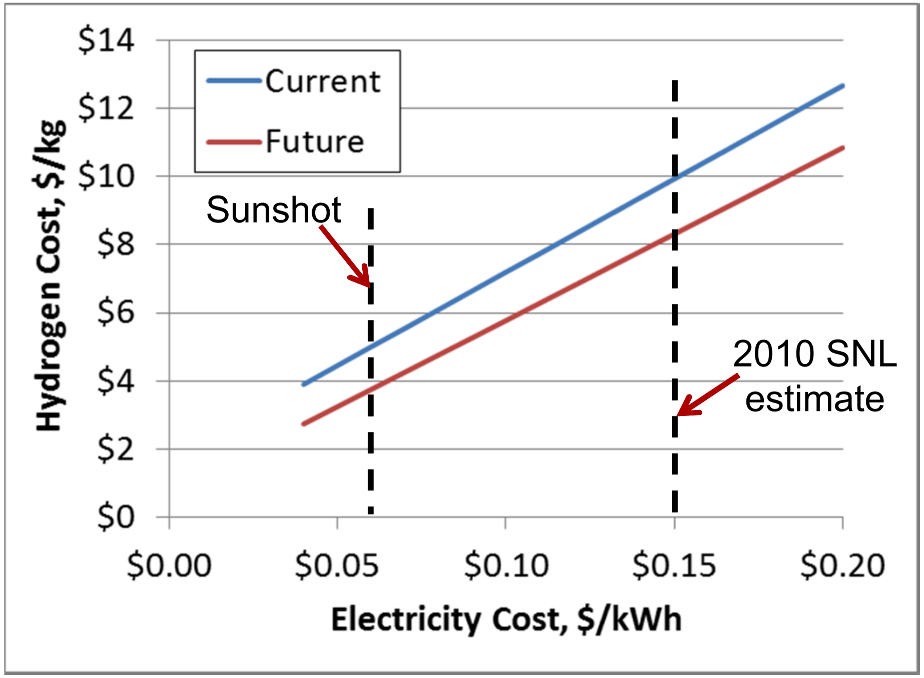

Results from H2A model of Hydrogen Production from PEM Electrolysis .

- H_2 production via PEM electrolysis requires low-cost electricity
  - Using 2010 SNL estimate of CSP costs ($0.15/kWh), H_2 cost is $8-10/kg
  - Using SunShot target ($0.06/kWh), H_2 cost is $3.75-$5/kg

HIGH-T ELECTROLYSIS

High-T electrolysis uses thermal energy to increase efficiency

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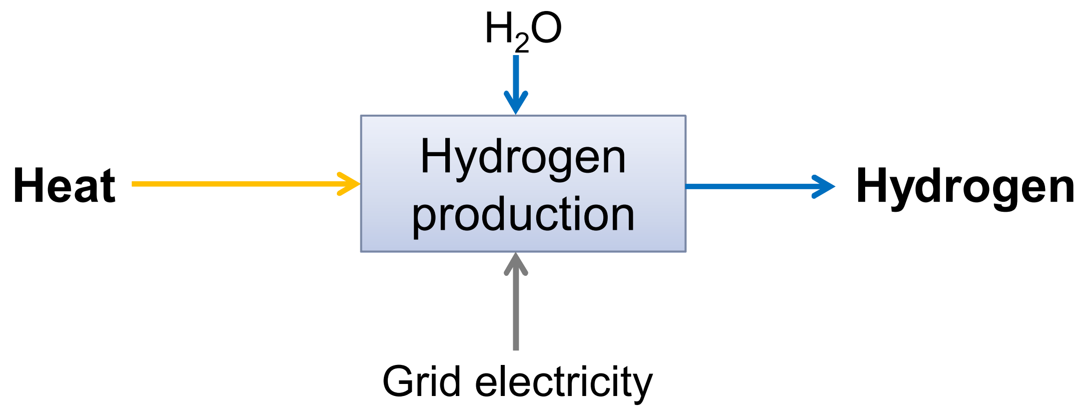
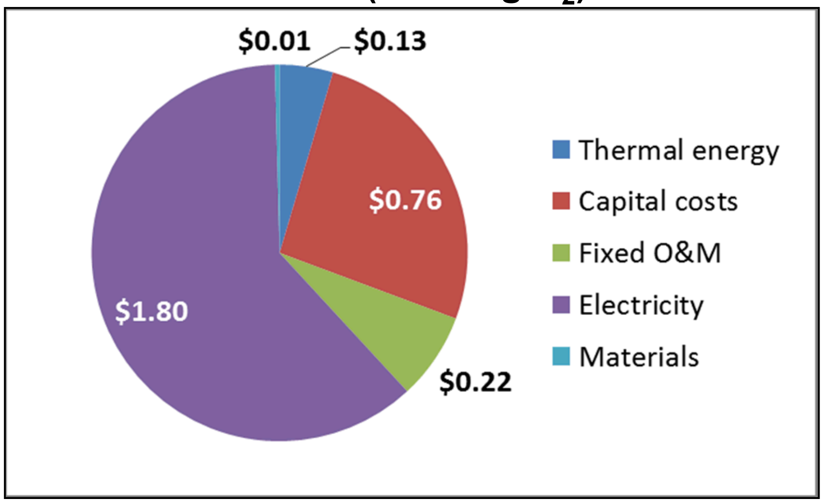
H2A analyses assume heat is supplied by a nuclear reactor*



- Thermal energy is used to raise the temperature of electrolysis
  → A portion of electrolysis energy can be supplied as heat

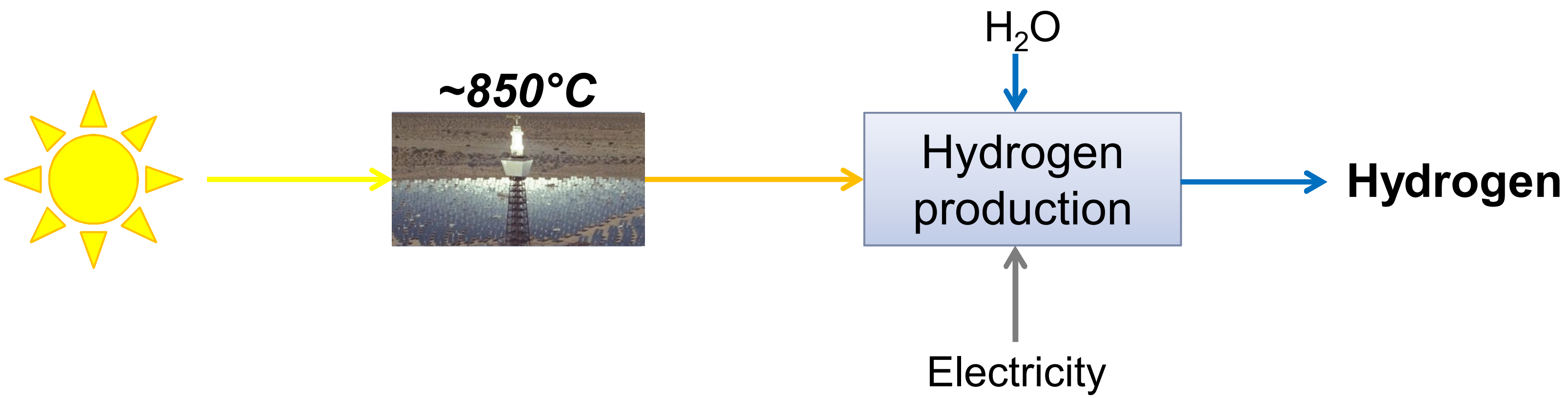
- Heat input is relatively low:
  6.8 kWh_T / kg H_2, versus
  electricity input of 33.2 kWh_e / kg H_2

Breakdown of costs ($2.93/kg H_2) for H2A case



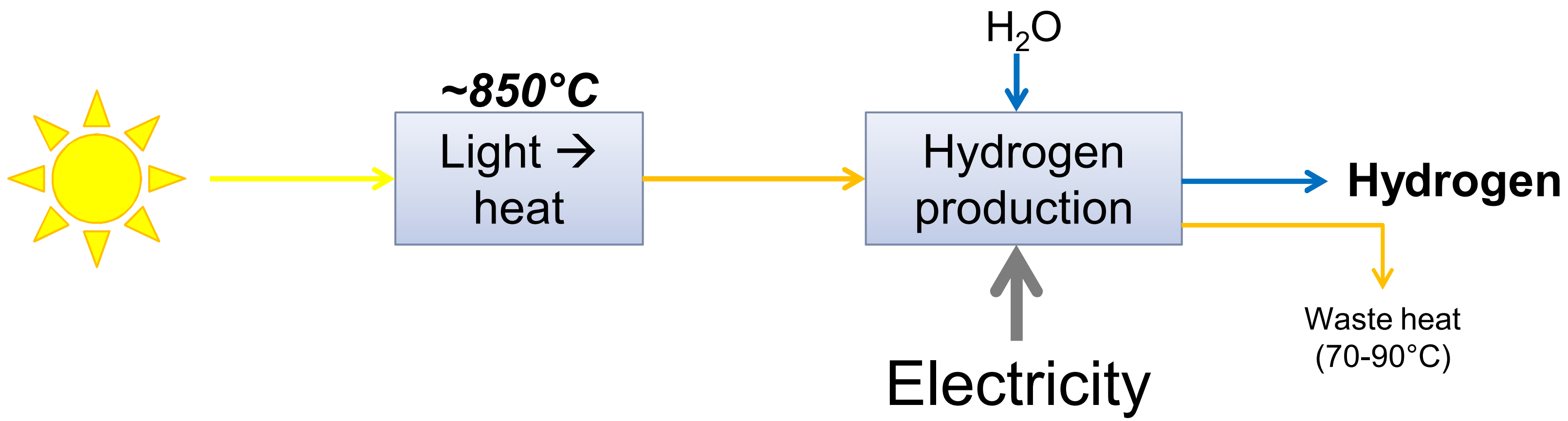
*Forthcoming H2A case will not specify source of thermal energy

Current analysis assumes solar thermal energy



- Assume solar receiver(s) with 340 MW_T output
  - Total amount of heat available is similar to H2A case (nuclear power)
- Solid particle receivers provide heat at ~850C (similar to nuclear reactor)

Current analysis assumes solar thermal energy



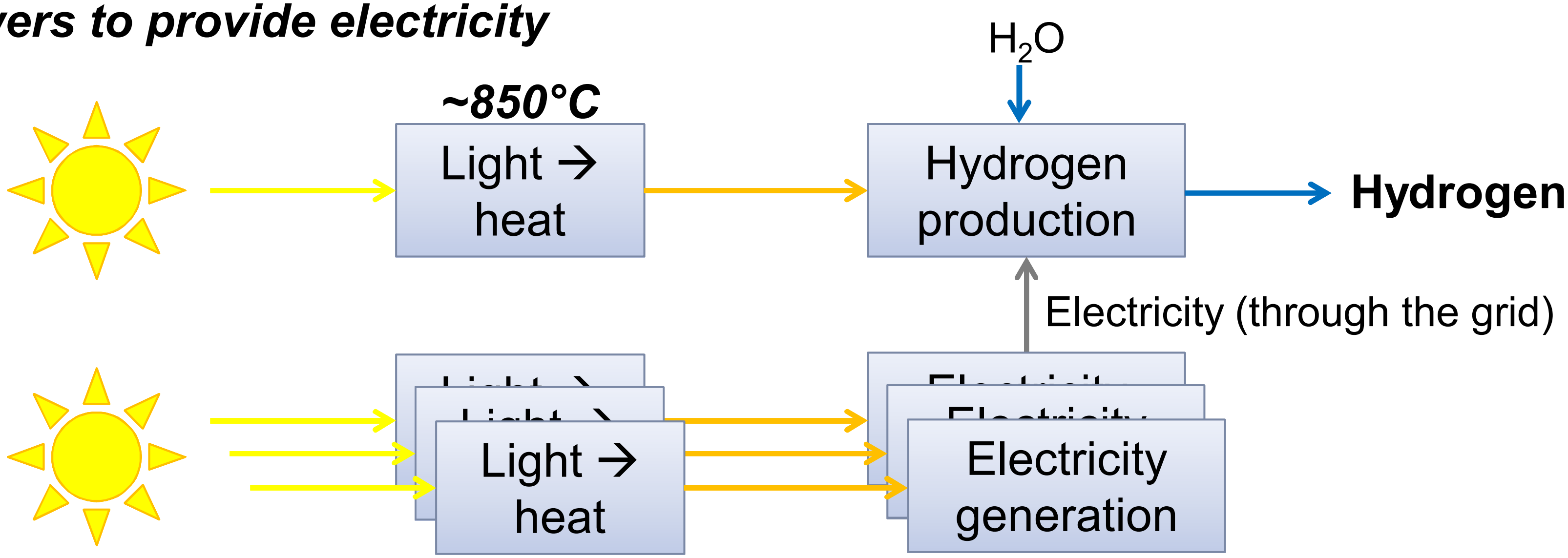
- Assume solar receiver(s) with 340 MW_T output
  - Total amount of heat available is similar to H2A case (nuclear power)
- Solid particle receivers provide heat at ~850C (similar to nuclear reactor)

Key Factors:

- Electricity consumption is high
- Process yields low-T waste heat

High-temperature electrolysis Case 1

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



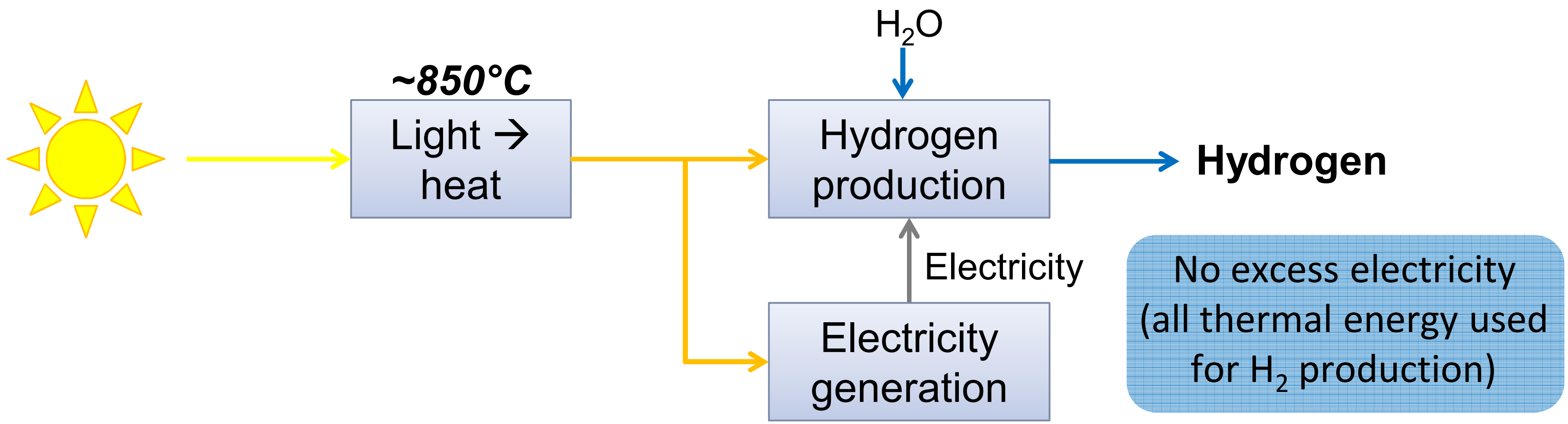
11 additional CSP towers would be necessary to supply necessary electricity for each tower supplying exclusively heat for H_2 production

Co-location of 12 large power towers may not be feasible
→ No process-level integration of H_2 production and CSP

Case 1 looks very similar to H2A case, with heat provided by solar energy rather than a nuclear reactor

High-temperature electrolysis Case 2

Single tower dedicated to Hydrogen production

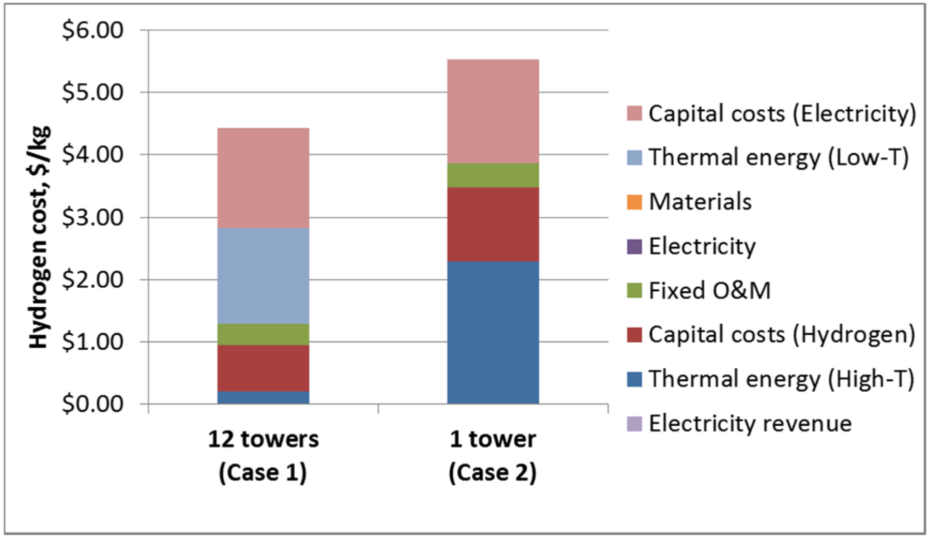


For Case 2, **9%** of thermal energy is used directly for H_2 production, **91%** of thermal energy is used for electricity generation
→ Total H_2 production is 80,000 kg/day

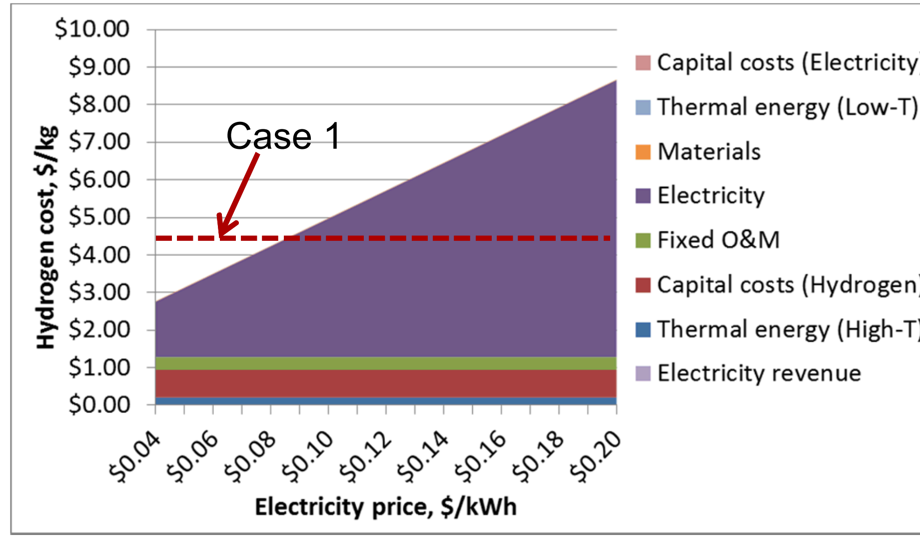
- Thermal energy for electricity gen is ≥650 C → Electricity generation efficiency ↑
- However, efficiency of thermal energy collection ↓

Trade-off: Power generation efficiency vs. thermal energy collection efficiency

12 towers vs 1 tower



12 towers (Case 1, internal electricity gen) vs H2A-like case (purchase electricity)



Case 1 reduces cost vs Case 2

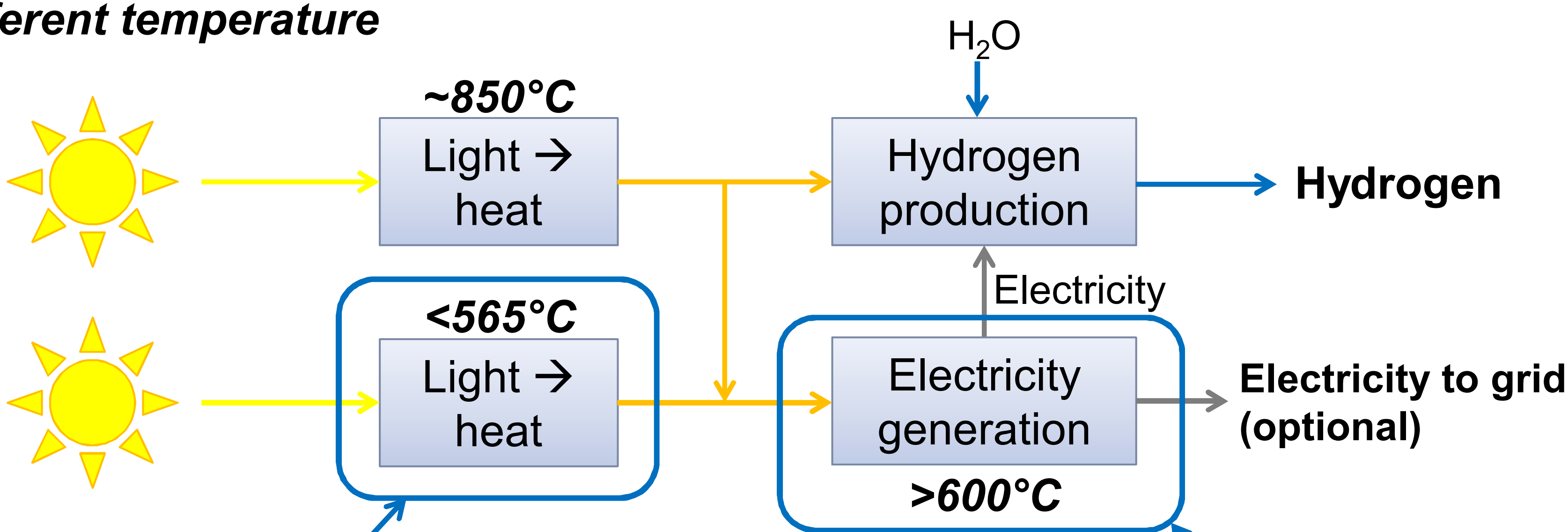
- Higher power generation efficiency in Case 2 is not sufficient
- Economies of scale and higher efficiency of thermal energy collection favor Case 1

Electricity cost is the primary driver for the H2A case (purchased electricity)

→ Cost of CSP vs grid electricity determines viability of CSP cases

High-temperature electrolysis Case 3

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



Solar thermal energy collection is more efficient at lower T

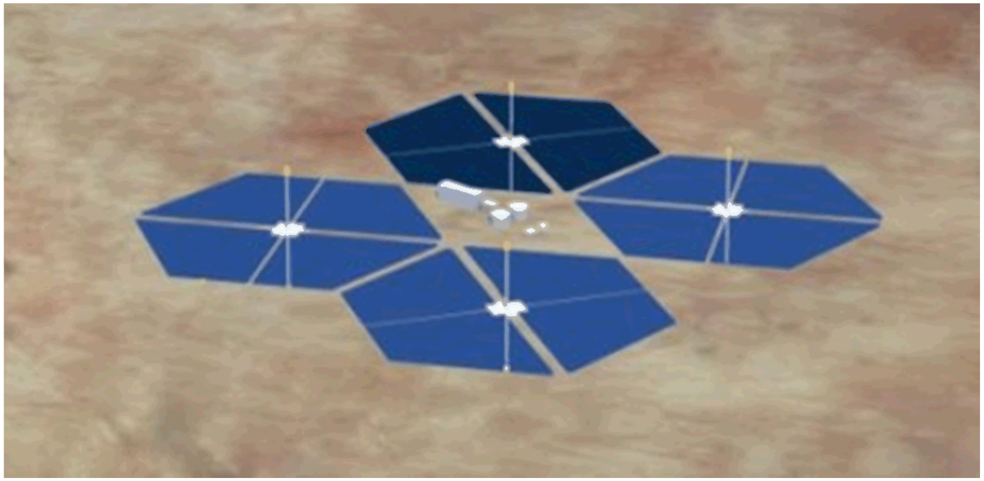
Electricity generation is more efficient at higher T
→ Electricity generation efficiency increases from **42%** to **48%**

- **18%** of thermal energy at 850C is used to raise electrolysis T
  → H_2 production is 160,000 kg/day
- Excess thermal energy from first tower and all thermal energy from the second tower is used for electricity generation

Combining heat from multiple small towers has precedent in industry

- eSolar has taken a modular approach for utility-scale solar power tower thermal plants
- Total plant output is deployed in 12MWT increments for direct steam, 50MWT increments for molten salt solar fields

→ Similar approach could be taken in collecting heat from multiple towers producing H_2 via metal oxide TC cycles



Source: www.eSolar.com

Operation of multiple towers at two different temperatures reduces H_2 cost

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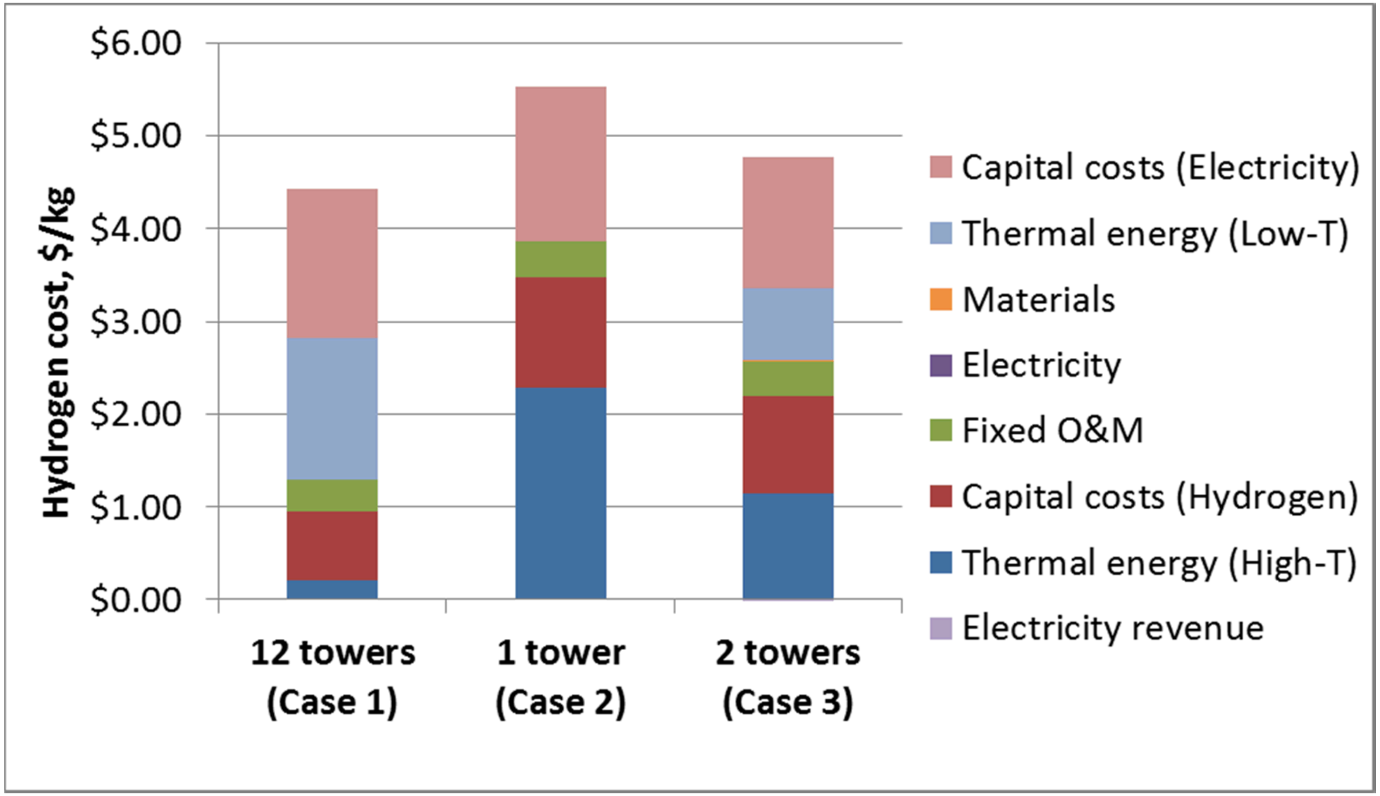


- Case 1 remains lowest cost due to large scale and efficient collection of thermal energy
- Case 3 reduces costs vs Case 2 due to increases in efficiency of thermal energy collection and conversion to electricity

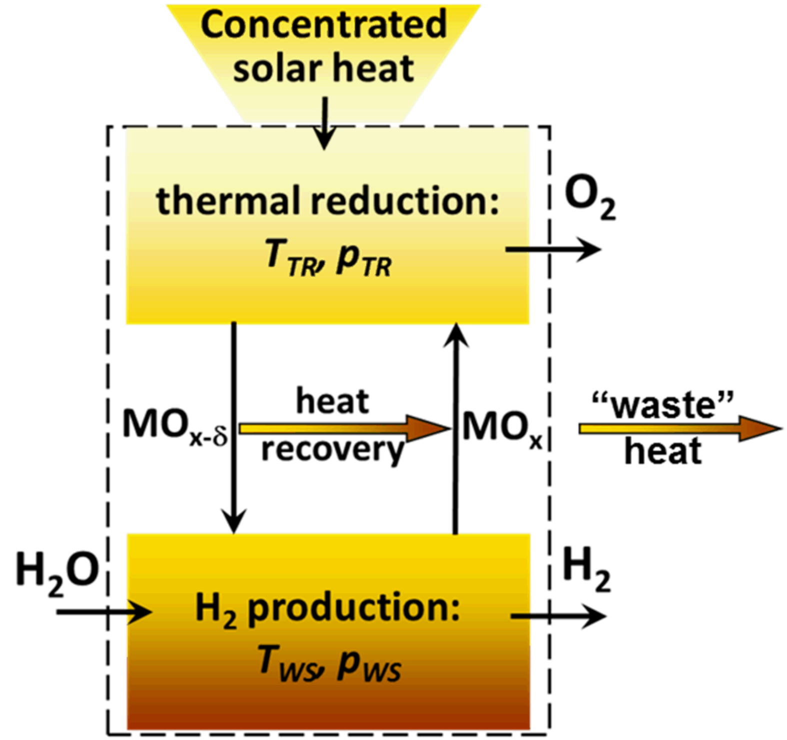
METAL OXIDE THERMOCHEMICAL HYDROGEN PRODUCTION

Metal oxide TC cycles convert thermal energy to chemical energy

- Solar thermal energy is utilized for thermal reduction of metal oxide particles at high T

- Thermal energy is rejected at high T (high-quality heat) between reduction chamber and H_2 production

→ Inefficiencies in heat recovery result in “waste” heat

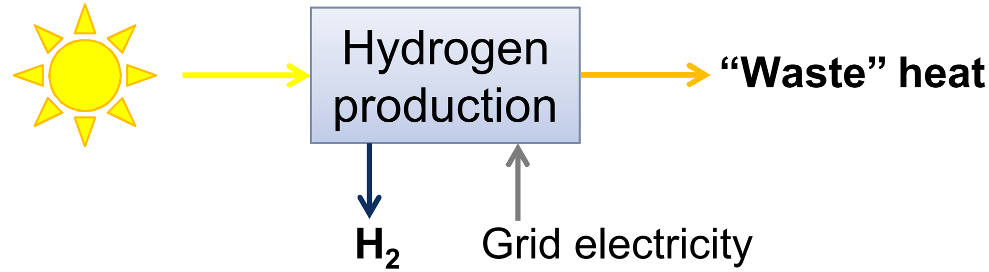


$$MO_X \rightarrow MO_{X-\delta} + \frac{\delta}{2} O_2 \quad \text{(thermal reduction, TR)}$$

$$MO_{X-\delta} + \delta H_2O \rightarrow MO_X + \delta H_2 \quad \text{(water splitting, WS)}$$

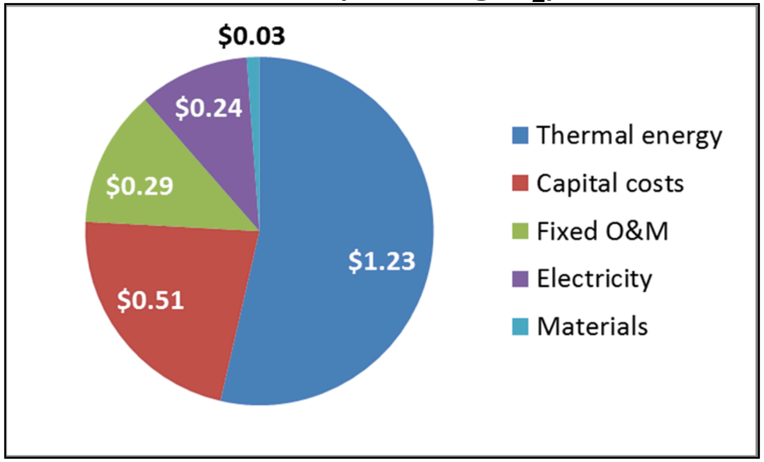
$$\delta H_2O \rightarrow \frac{\delta}{2} O_2 + \delta H_2 \quad \text{(net reaction)}$$

Metal oxide TC cycle Case 1: Electricity purchased from the grid



- Analysis is based on H2A assumptions
  - Temperatures of reduction (1500C) and H_2 production (1150C) were fixed
  - Metal oxide: Ceria
  - 231 small 4.24 MW_T towers (*vs.* one large 1000 MW_T tower for CSP)
- **"Waste" heat is not utilized in the Solar Thermo-Chemical H2A Case Study → Case 1 is similar to H2A case**

Breakdown of costs ($2.29/kg H_2) for H2A case

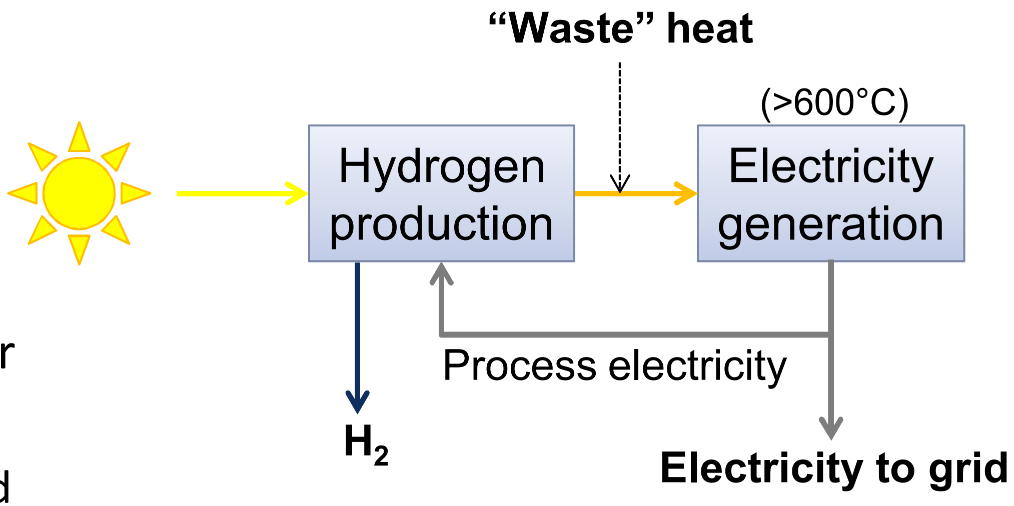


Source: "Ultimate" Central Hydrogen Production from Solar Thermo-Chemical Cycle, H2A Case Study

Because waste heat is not utilized to generate power, electricity must be purchased from the grid

Metal oxide TC cycle Case 2: Internal power generation from waste heat

- Waste heat is used to generate power for internal use
- Electricity generation is sufficient to meet process power needs
  - Small excess may be sold to grid



No need to purchase grid electricity, but smaller scale of power generation reduces efficiency and increases cost compared to full-scale CSP

Electricity generation from waste heat reduces H_2 cost if electricity price is >$0.07/kWh

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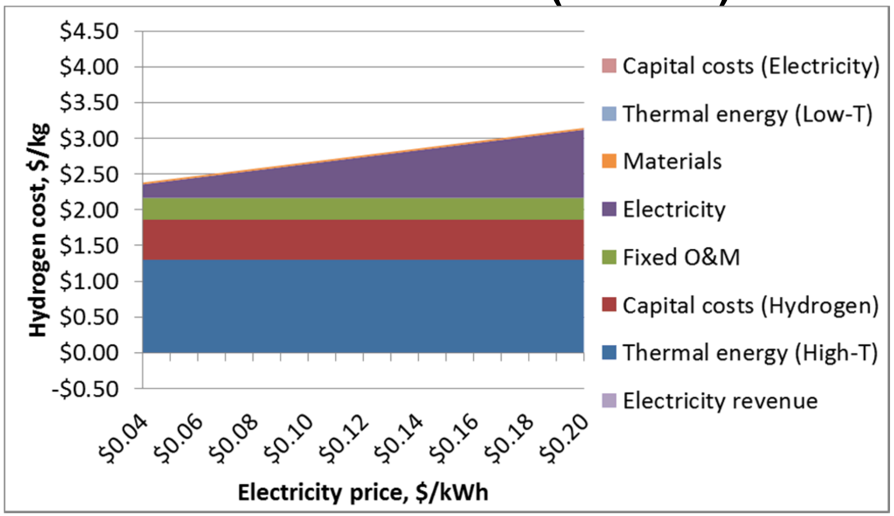
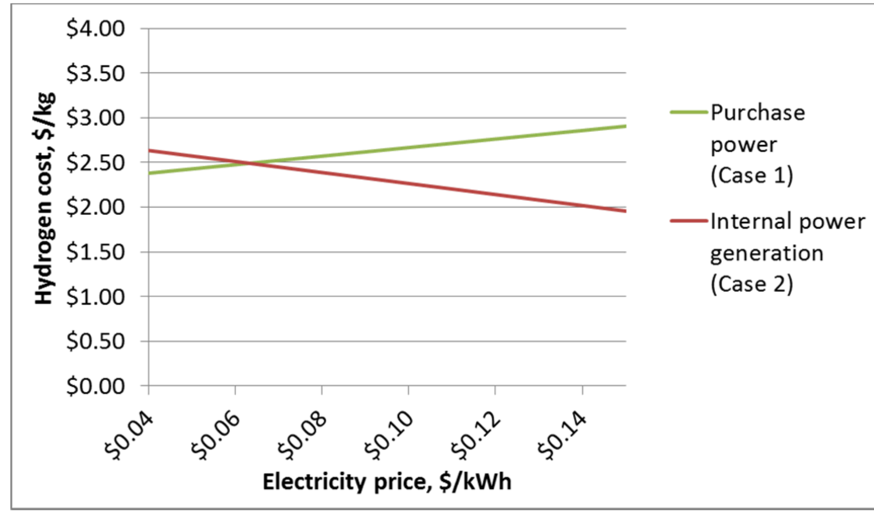
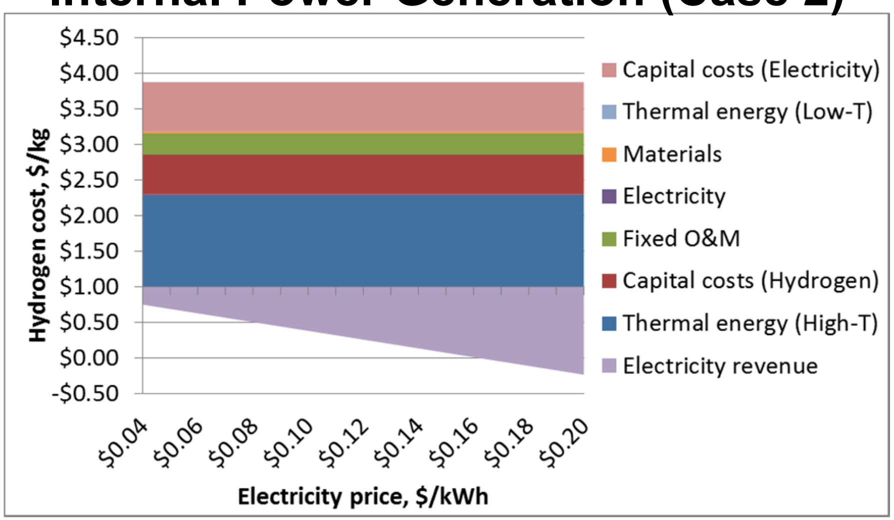
Purchase Power (Case 1)





Internal Power Generation (Case 2)



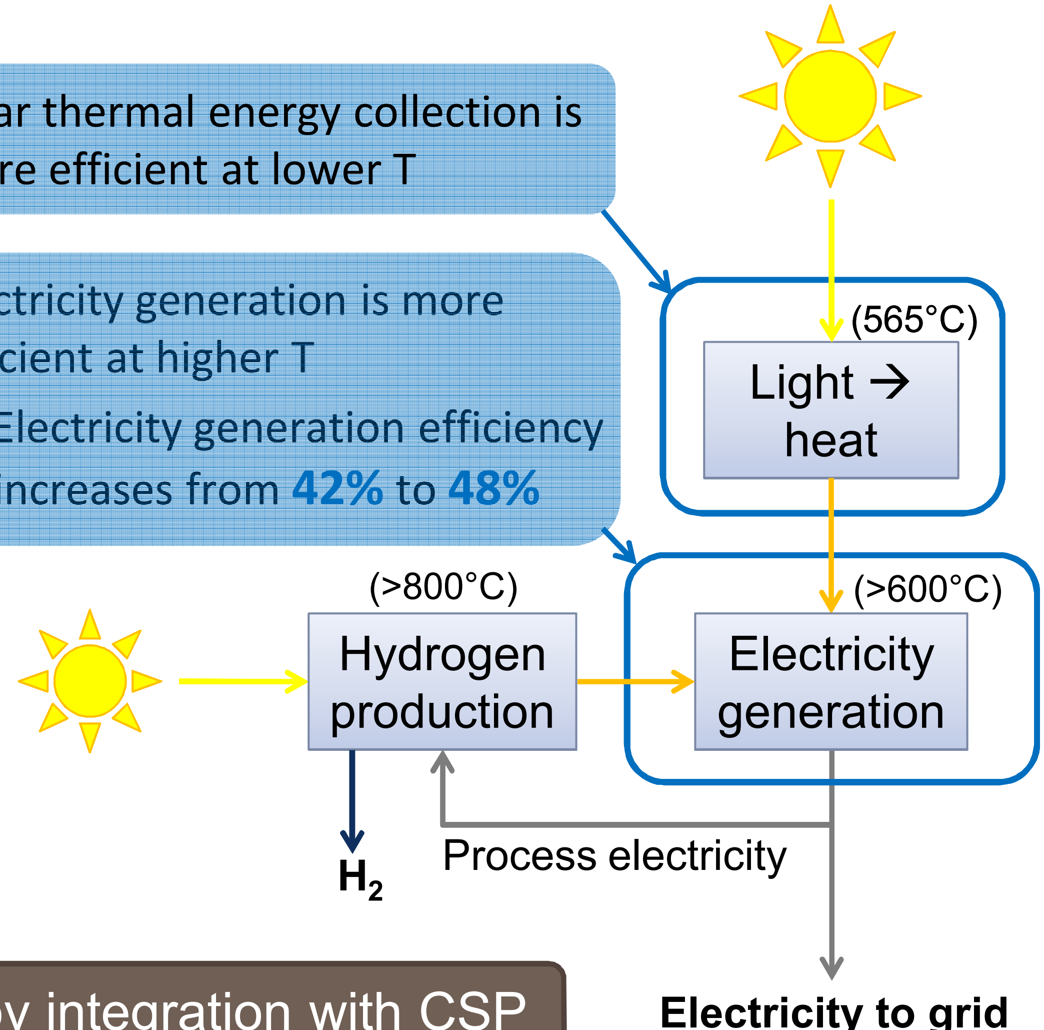
Electricity is a relatively small cost for metal oxide TC cycles
→ Benefits of internal power generation become more significant as electricity price exceeds $0.10/kWh

Metal oxide TC cycle Case 3: Integration with CSP

- Combine excess thermal energy with thermal energy from a CSP tower
- Temperature of electricity generation is raised
- Note: If H_2 production and CSP were integrated, full system optimization would be performed
  → **Outside current scope of analysis**
  - Analysis is based on H2A assumptions

Solar thermal energy collection is more efficient at lower T

Electricity generation is more efficient at higher T
→ Electricity generation efficiency increases from **42%** to **48%**



Value of waste heat is amplified by integration with CSP

Waste heat from H_2 production has high potential value as a CSP "feedstock"

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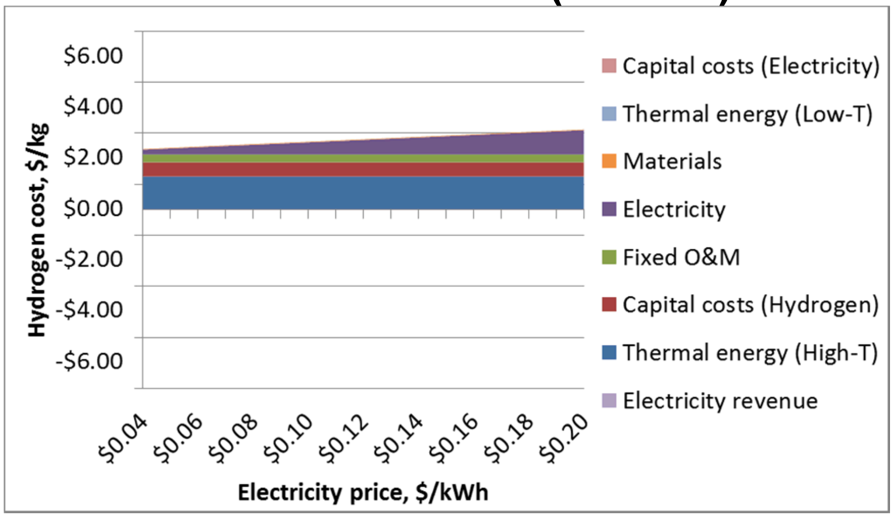
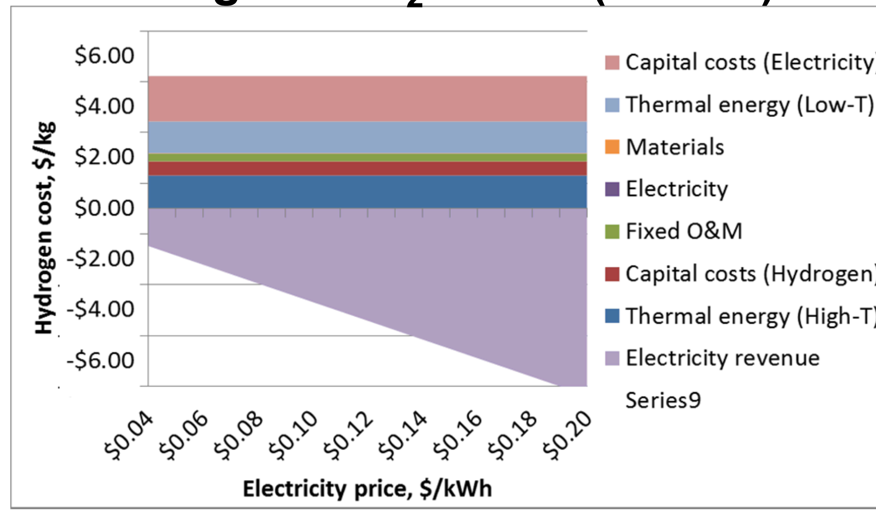
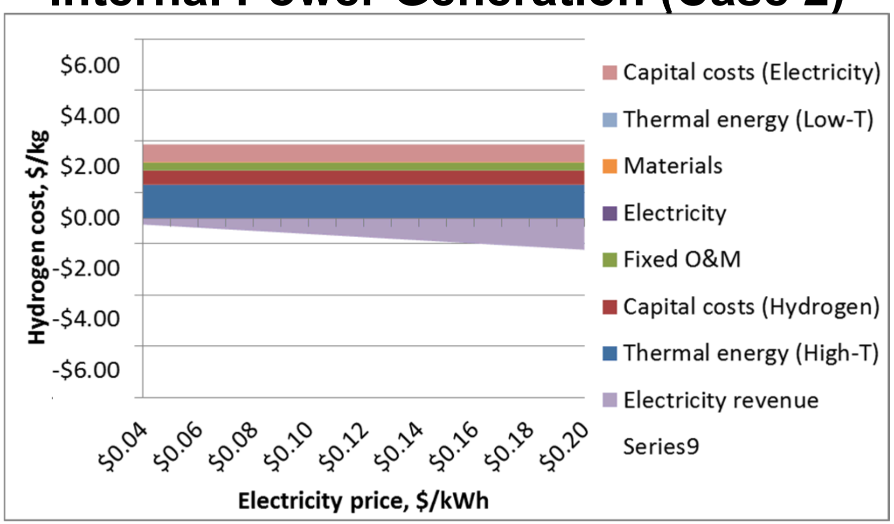
Purchase Power (Case 1)

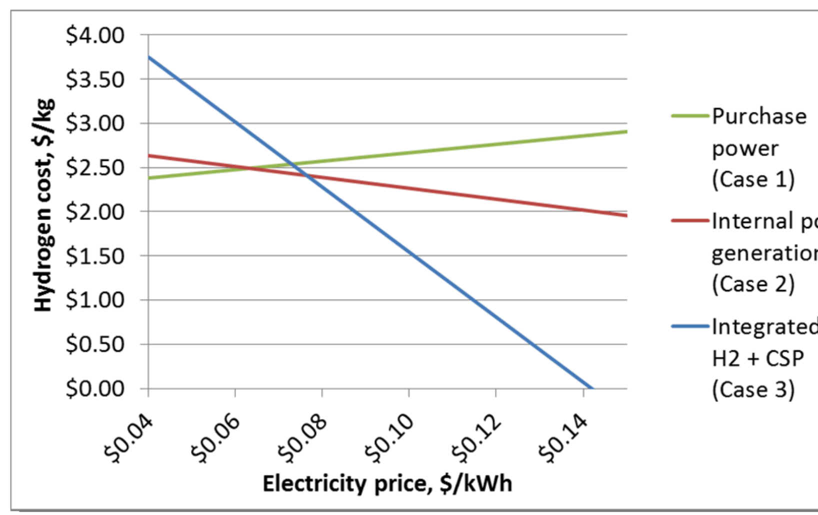


Integrated H_2 + CSP (Case 3)



Internal Power Generation (Case 2)





Thought experiment: Adjacent H_2 and CSP plants

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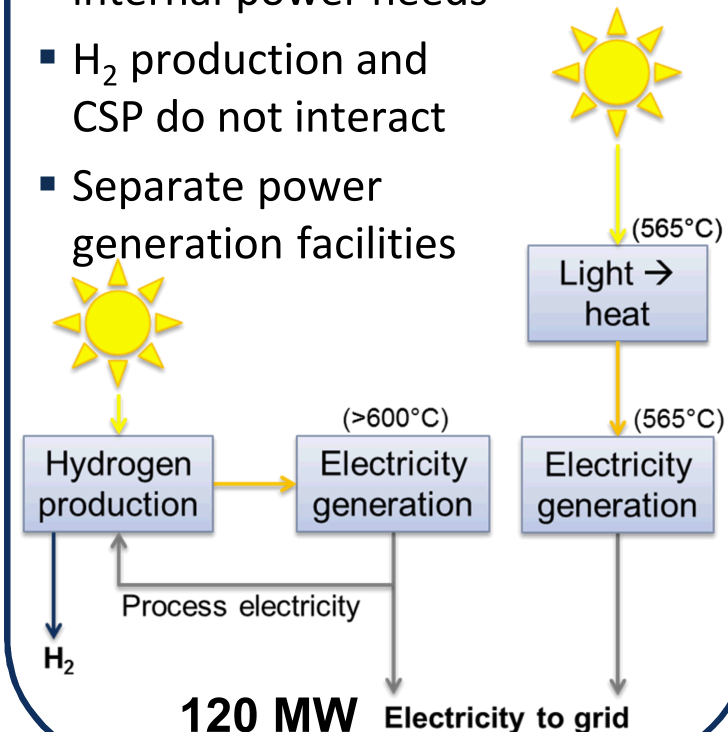
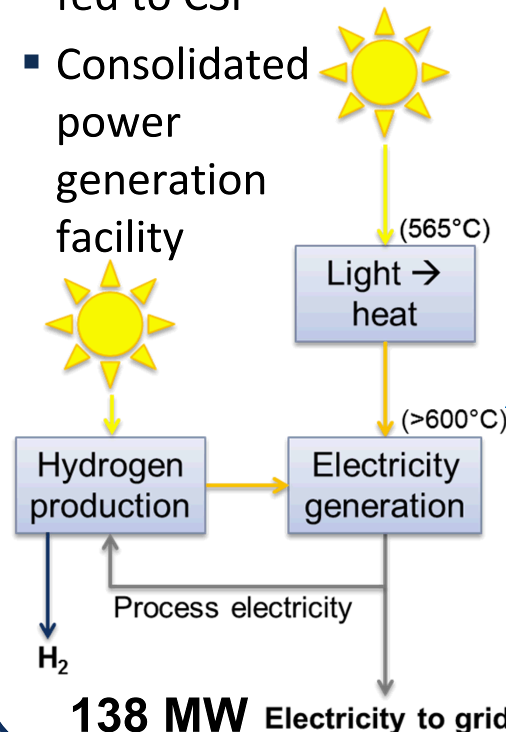
No integration

- Waste heat supplies internal power needs
- H_2 production and CSP do not interact
- Separate power generation facilities



CSP-H_2 integration

- Waste heat is fed to CSP
- Consolidated power generation facility



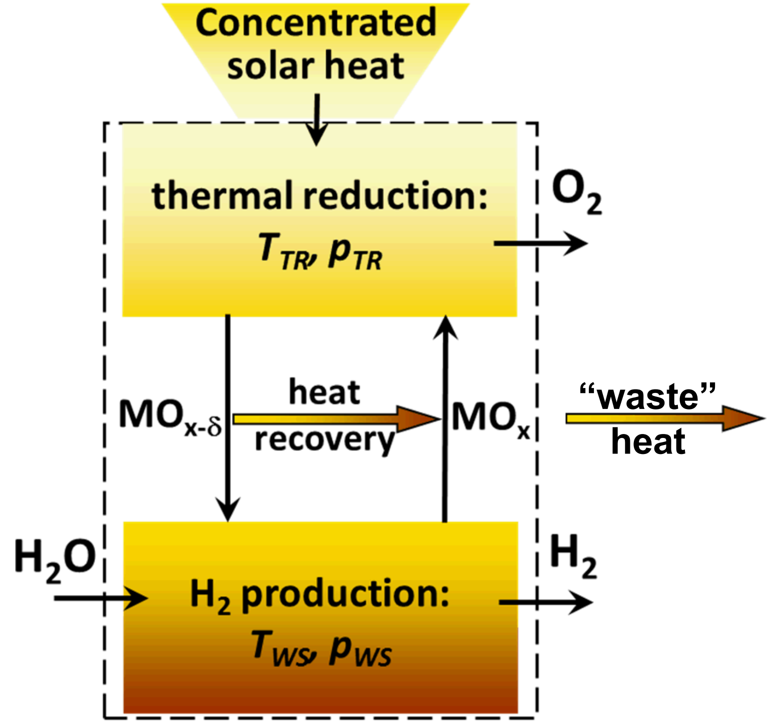
Electricity generation efficiency increases from **42%** to **48%** at higher T

****All heat*** is converted to electricity more efficiently, not only heat from H_2 production

CSP-H_2 integration increases electricity generation by 15% (relative), with lower total capital costs

The "optimal" MOTC cycle maximizes H_2 production efficiency

- The "optimal" case assumes efficient heat recovery, higher H_2 production temperature (1150 C)
  - "Waste" heat is minimized
- A second case features lower H_2 production temperature (800 C) and less efficient heat recovery
  - More "waste" heat is available



$$MO_X \rightarrow MO_{X-\delta} + \frac{\delta}{2} O_2 \quad \text{(thermal reduction, TR)}$$

$$MO_{X-\delta} + \delta H_2O \rightarrow MO_X + \delta H_2 \quad \text{(water splitting, WS)}$$

$$\delta H_2O \rightarrow \frac{\delta}{2} O_2 + \delta H_2 \quad \text{(net reaction)}$$

More “waste” heat increases electricity production

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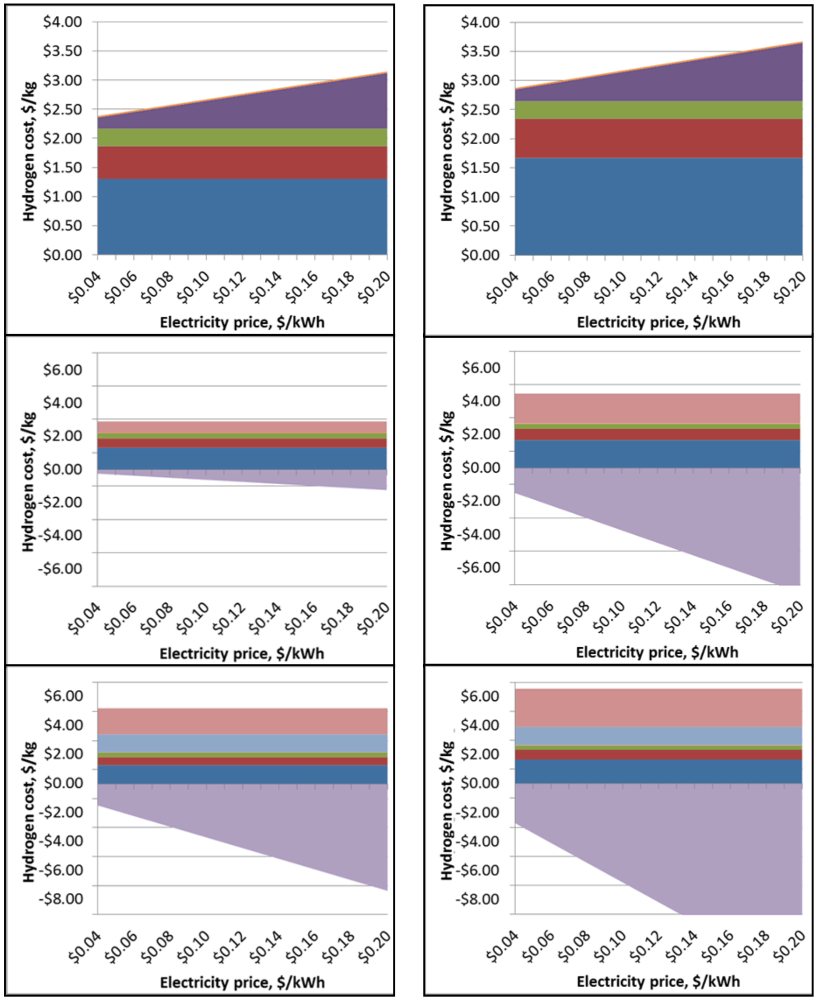
“Optimal” case | **More “waste” heat**

Purchase Power (Case 1)

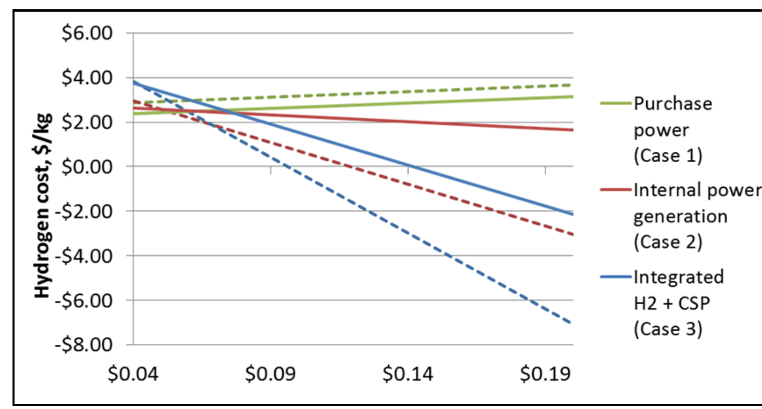
Internal Power Generation (Case 2)

Integrated H_2 + CSP (Case 3)



Larger thermal energy input, higher capital costs
→ Higher H_2 production cost

Larger thermal energy input and higher capital costs (H_2 & electricity),
But increased electricity revenue



Solid lines: “Optimal” case;
Dashed lines: More “waste” heat

- Capital costs (Electricity)
- Materials
- Fixed O&M
- Thermal energy (High-T)
- Thermal energy (Low-T)
- Electricity
- Capital costs (Hydrogen)
- Electricity revenue

Outline

- Introduction
  - Background
  - Modeling approach
  - Key assumptions
  - Concentrating solar power (CSP) overview
  - General comments on CSP-H_2 integration
- CSP-H_2 integration scenarios
- **Conclusions and insights**

A few words about uncertainty and sensitivity of results

- Solar H_2 technologies are at an early stage of development
  - Costs and performance are highly uncertain
  - Detailed optimizations are premature
- The key analysis results are the set of insights regarding favorable conditions for CSP-H_2 integration
- These results (insights) are robust
  - Insights are driven by inherent characteristics of processes
  - Specific conditions favorable to integration are impacted by the *relative* costs of CSP and grid electricity
  - Insights are unaffected by absolute H_2 production costs (excluding electricity costs)

General conclusions

- Collection of solar thermal energy is a significant cost for both CSP and solar H_2 production
  - Heat integration is a potential strategy for improving the performance of both CSP and H_2 production
  - Optimal temperature of CSP is lower than that for H_2 production
- CSP yields no high-T waste heat or significant material byproducts
  - Necessary to look for potential heat flows from H_2 production to CSP
- Electricity prices have a significant impact on the analysis results
  - From the perspective of H_2 production, CSP-H_2 integration is favored when CSP price is lower than electricity price
- H_2 production via PEM electrolysis offers no significant potential for integration with CSP
  - No input of thermal energy required
  - No waste streams of potential value for CSP
- Economics of PEM electrolysis are primarily driven by electricity price

Conclusions: High-T electrolysis

- A relatively small input of heat is required compared to electricity needs of high-T electrolysis
  - No high-T waste heat is available from H_2 production

- Integration of multiple towers for combined H_2 + electricity production is potentially attractive
  - More efficient collection and conversion of thermal energy
  - Excess heat from high-T tower can be diverted to raise the efficiency of electricity production by 15% (relative)
    - Diverting high-T heat to power generation will decrease thermal energy collection efficiency
  - Case-by-case optimization will be required to determine lowest-cost configuration

Conclusions: Metal Oxide TC cycles

- For metal oxide TC cycles, high-quality “waste” heat may be available in larger quantities than is needed for internal electricity generation
  - Electricity demand of MO TC cycles is relatively small
  - Internal electricity generation using waste heat has minimal impact for low to moderate electricity prices
- Integration of MO TC cycles and separate CSP tower is potentially attractive
  - Impact of high-T waste heat is amplified by integration with CSP
  - Efficiency of electricity generation could be increased by 15% (relative)
→ Waste heat from H_2 production has high potential value as CSP feedstock
- Future metal oxide TC cycles assume reductions in inert material, high recuperation of high-T heat
  - Current metal oxide TC cycles may generate significantly more waste heat
→ Increased potential for electricity revenue as a bridge to future development

Acknowledgements

- Cliff Ho, Sandia National Laboratories (CSP)
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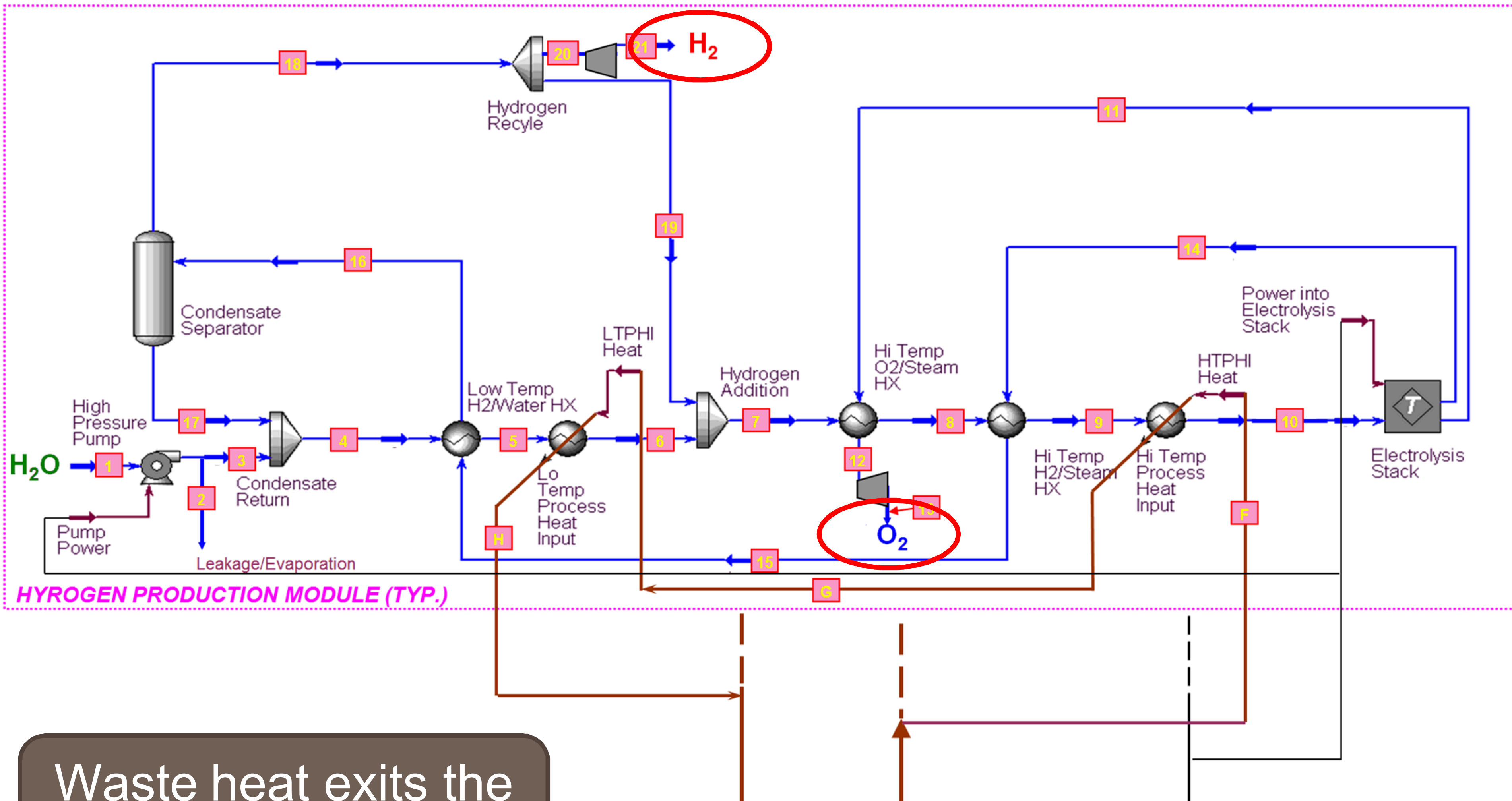
- Jim Ellison, Sandia National Laboratories (Electricity prices)

Additional Slides

High-T electrolysis waste heat streams are of low-quality



Heat transfer media return

Heat transfer media input

Electricity input

Waste heat exits the process at ~70-90°C