NATIONAL RENEWABLE ENERGY LABORATORY

Solar Industrial Process Heat Potential – A California Highlight

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EPRI and IEA Workshop – Renewables and Clean Energy for Industries

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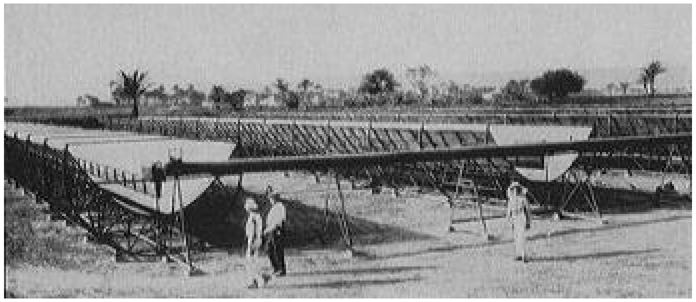
Presentation Outline

- Background and Motivation
- Current Costs of Parabolic Trough Collectors
- Industrial Heat and Steam Demands in the U.S.
- SIPH potential in California
- Can SIPH compete with natural gas?
- Challenges and Opportunities
- Conclusions

Background and Motivation

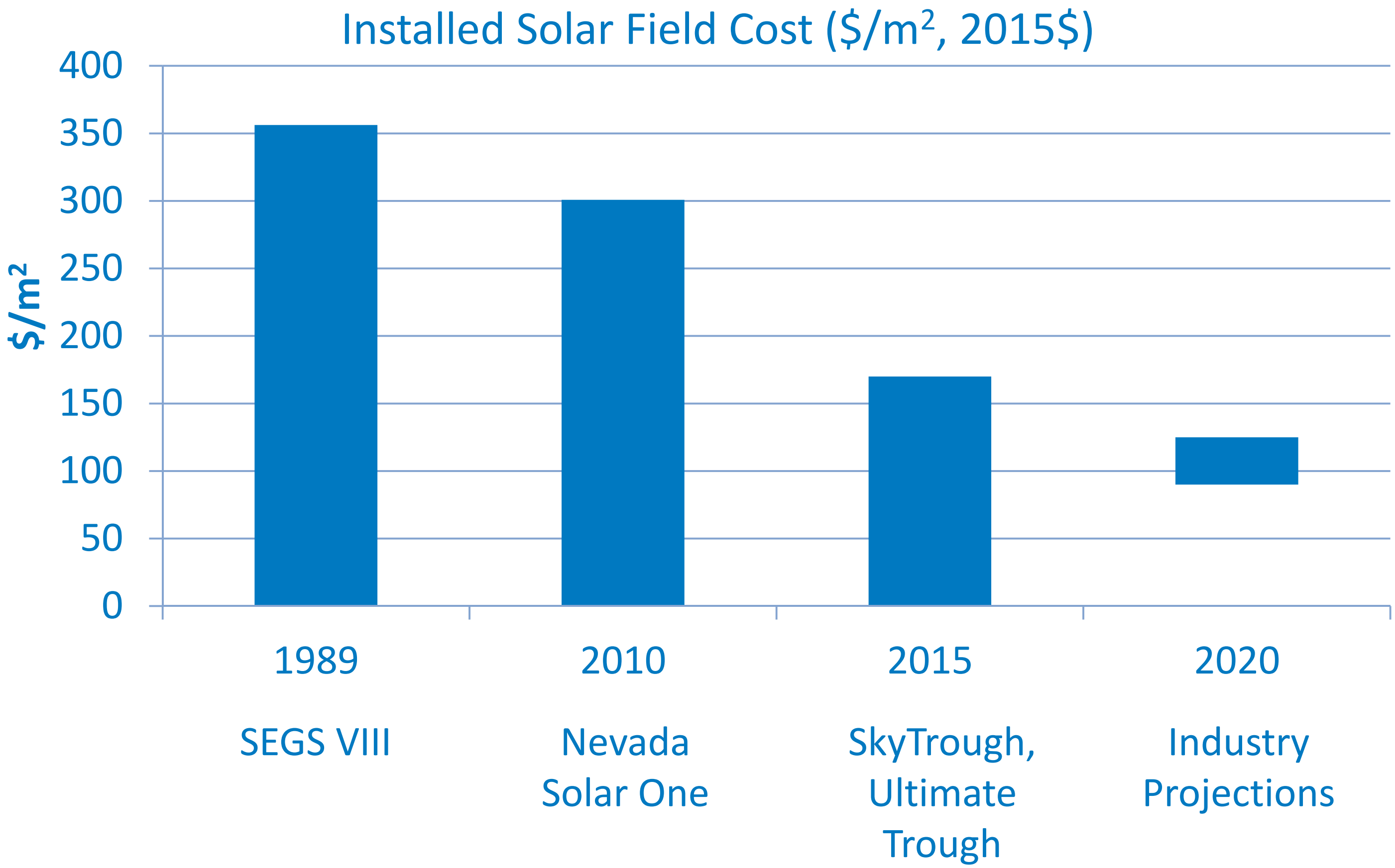
Background and Motivation

- 1913: Shuman trough plant built in Egypt!
- 1977: IEA Solar Heating and Cooling (SHC) Program setup
- 1980s: Interest in SIPH in response to the Oil Crisis
    - 1982 SERI/NREL publishes SIPH manual. Heat essential to industries
    - Payback period typically too long due to collector costs
- 1990: Parabolic trough plants deployed globally for power
    - Large improvements in performance; costs fall
- IEA SHC and SolarPaces Programs setup Task 49/IV
    - To help meet the potential of Solar Industrial Process Heat (SIPH)
    - Today's uptake of SIPH using concentrating collectors still low. ~25 plants as of 2016
- Current: Increasing global interest in solar thermal for heat
    - e.g., Enhanced Oil Recovery (EOR), Desalination, and IPH



Current Cost of Parabolic Trough Collectors

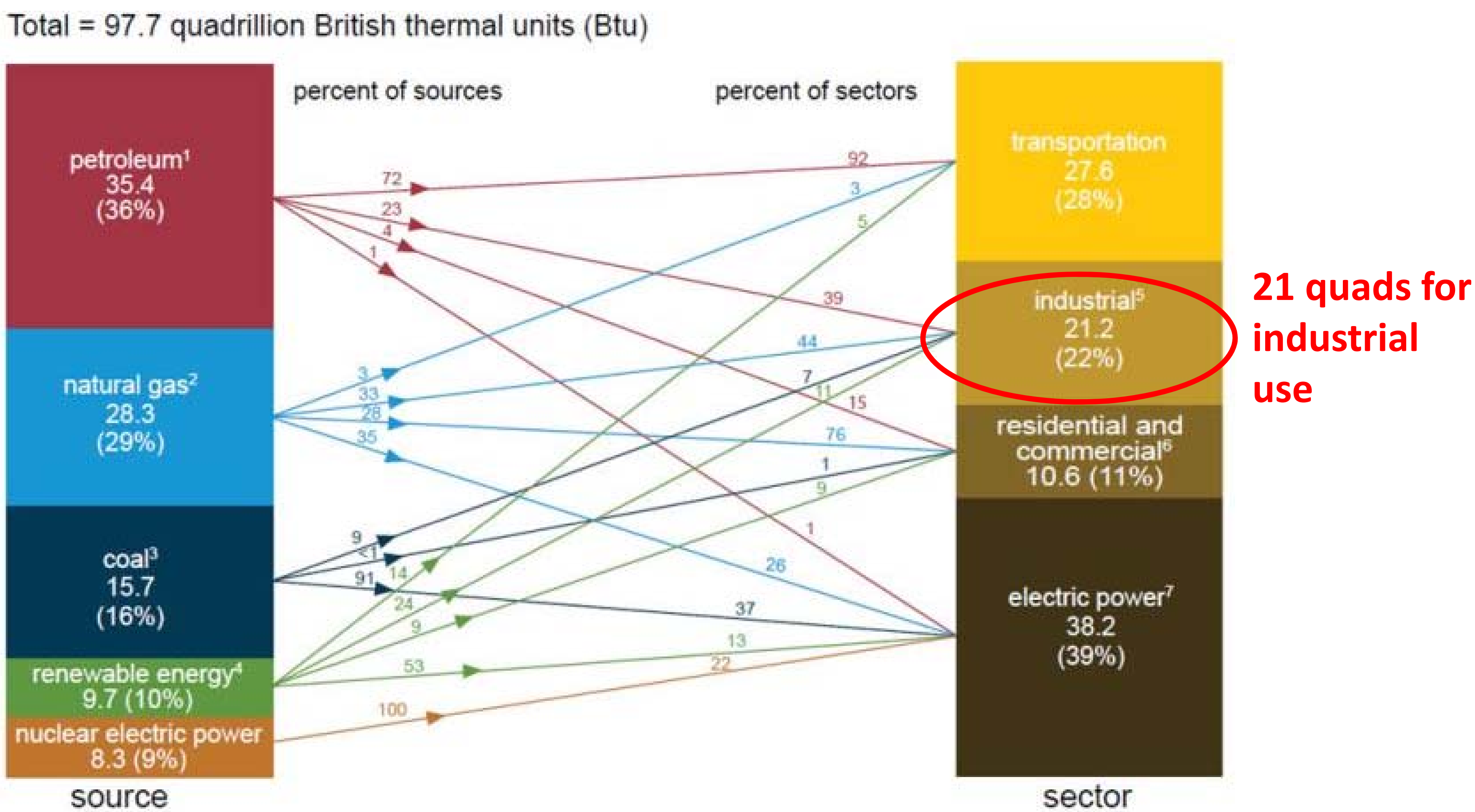
Parabolic Trough Cost History (according to NREL)



References:
- Sargent & Lundy, NREL/SR-550-34440 (2003)
- Kutscher et al., Line-Focus Solar Power Plant Cost Reduction Plan, NREL/TP-5500-48175 (2010)
- Kurup & Turchi, NREL/TP-6A20-65228, (2015)
- CSP Industry Workshop, Sacramento, CA (2015)

Industrial Heat and Steam Demands in the U.S.

U.S. Primary Energy Consumption, 2015



[1] Does not include biofuels that have been blended with petroleum—biofuels are included in "Renewable Energy."
[2] Excludes supplemental gaseous fuels.
[3] Includes less than -0.02 quadrillion Btu of coal coke net imports.
[4] Conventional hydroelectric power, geothermal, solar/photovoltaic, wind, and biomass.
[5] Includes industrial combined-heat-and-power (CHP) and industrial electricity-only plants.
[6] Includes commercial combined-heat-and-power (CHP) and commercial electricity-only plants.
[7] Electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public. Includes 0.2 quadrillion Btu of electricity net imports not shown under "Source."

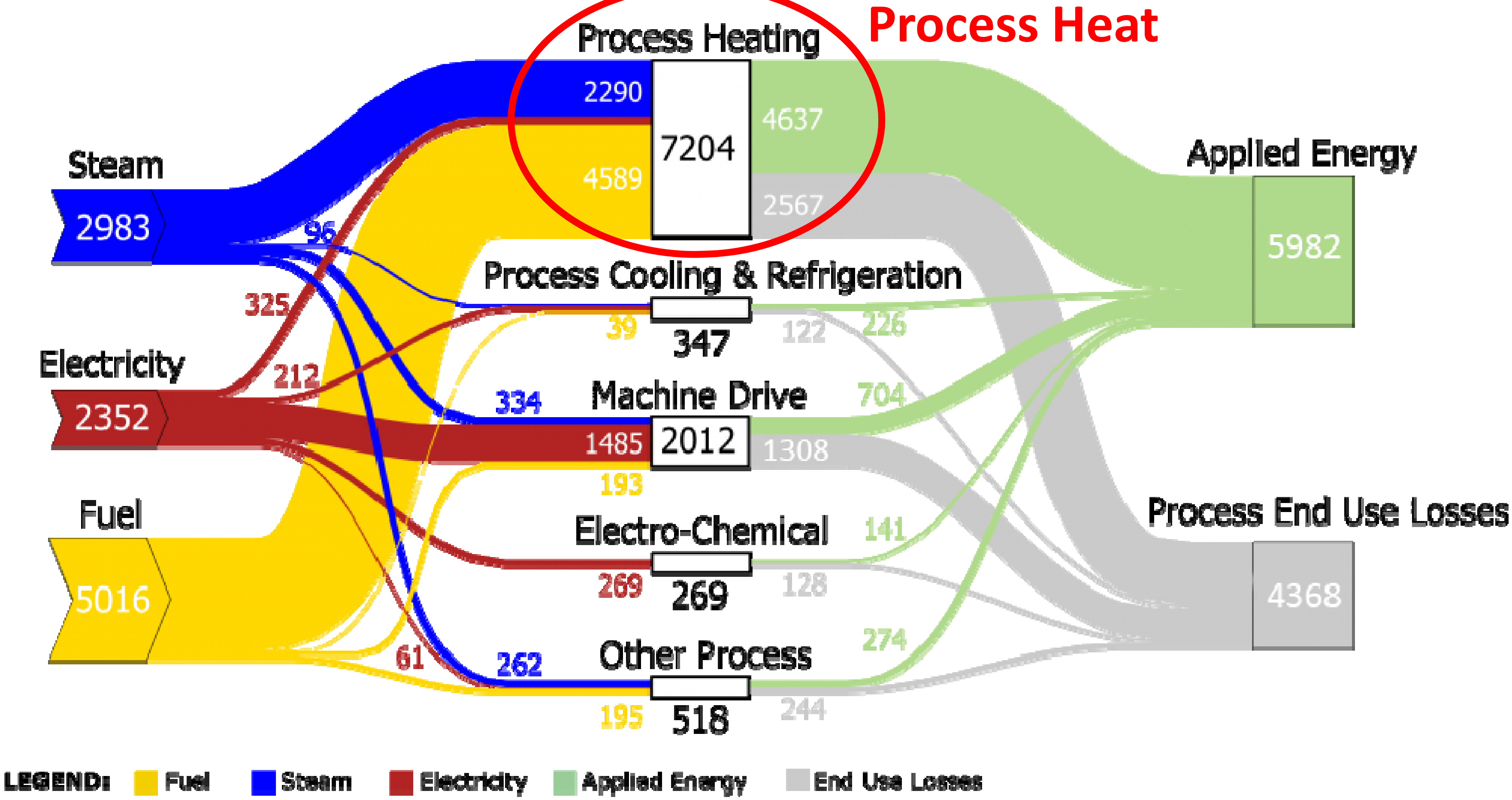
Notes: Primary energy in the form that it is first accounted for in a statistical energy balance, before any transformation to secondary or tertiary forms of energy (for example, coal is used to generate electricity). Sum of components may not equal total due to independent rounding.

Sources: U.S. Energy Information Administration, *Monthly Energy Review* (April 2016), Tables 1.3, 2.1-2.6.

U.S. Process Energy, MECS 2010

Values in TBtu

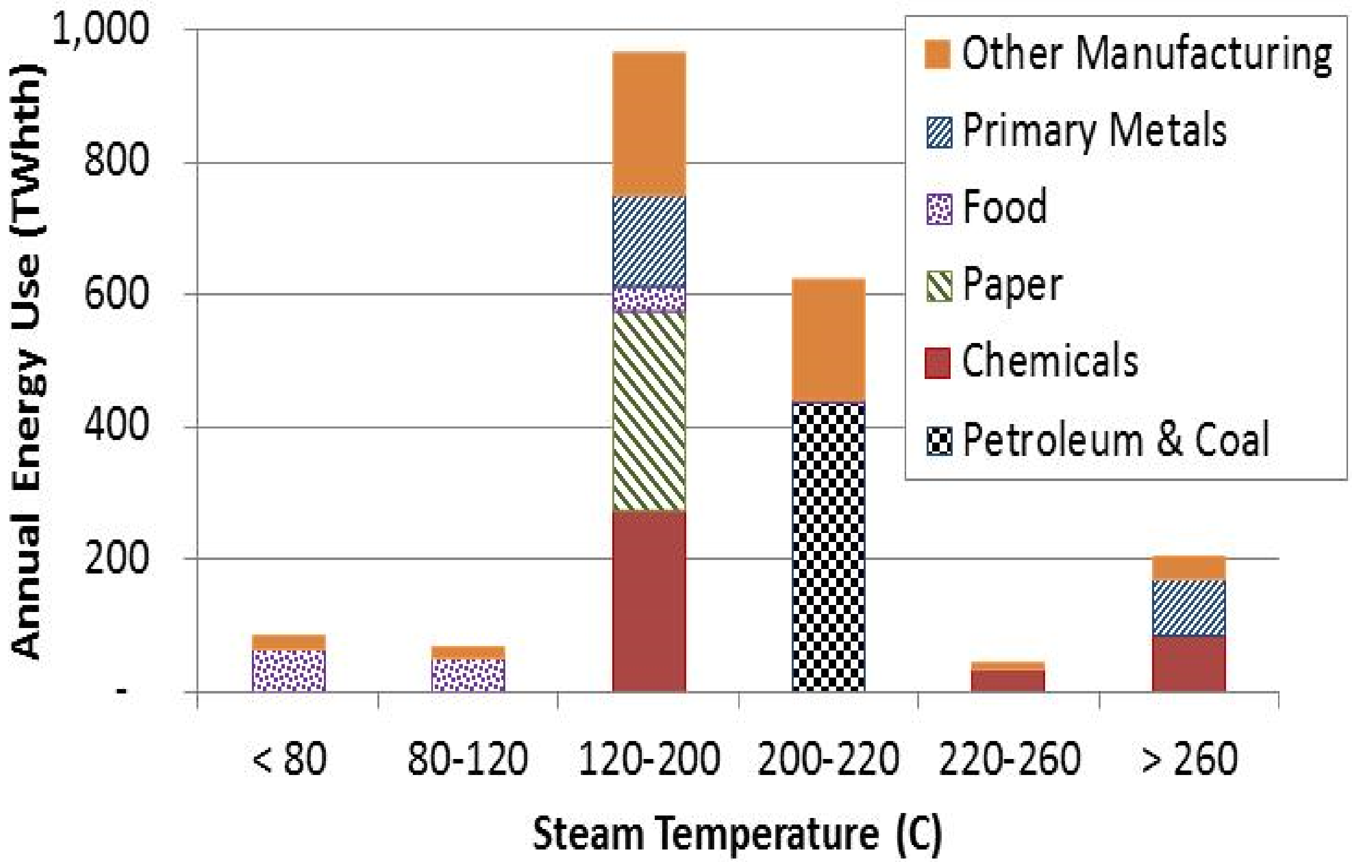
7.2 quads for Industrial Process Heat



MECS is the Manufacturing Energy Consumption Survey. 2010 was the last full complete dataset

eia.gov

Industrial Steam Use in the U.S.



⇨ **120-220 °C steam is target for solar IPH**

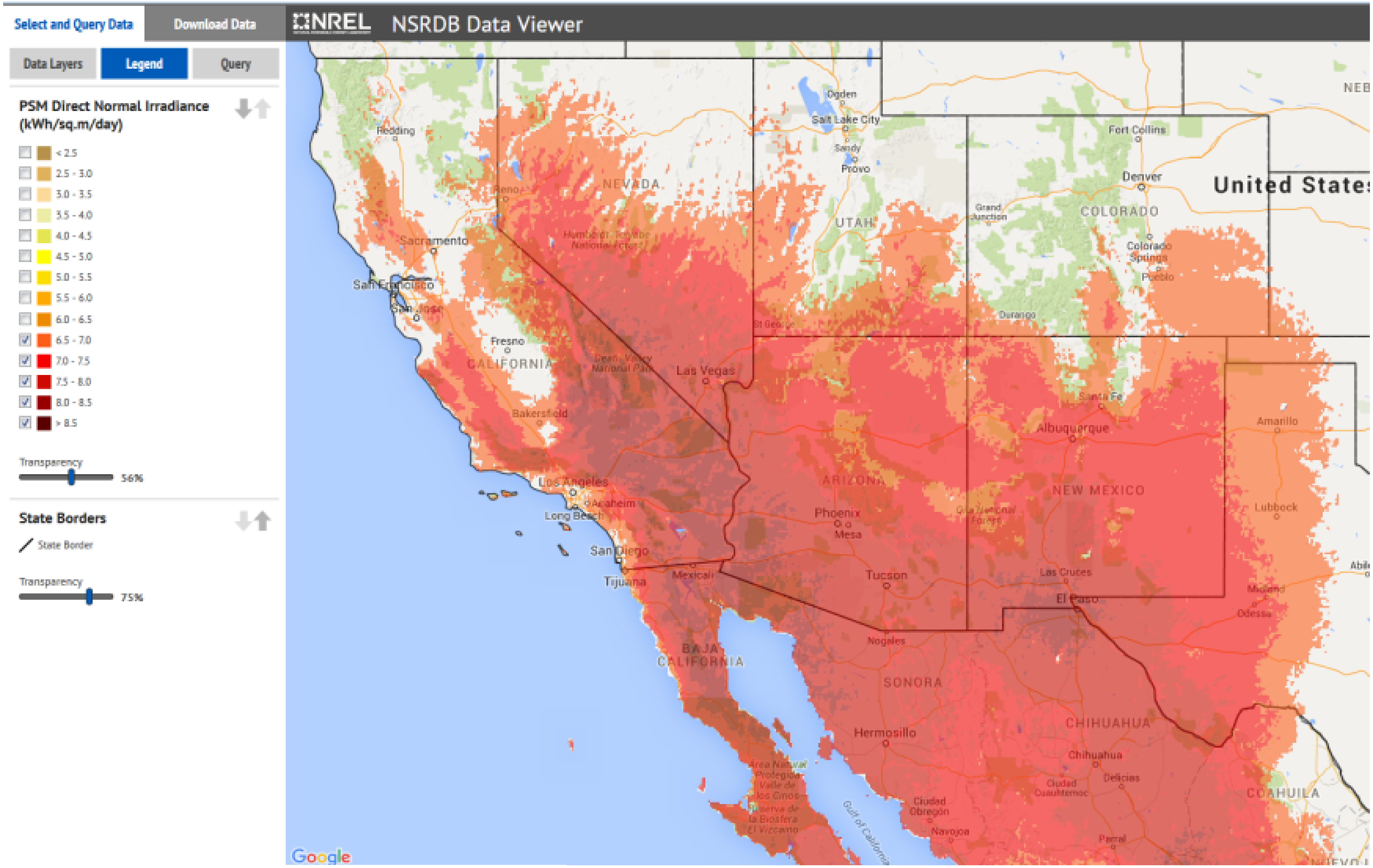
Fox, Sutter, and Tester, "The Thermal Spectrum of Low-Temperature Energy Use in the United States." 2011

CSP Configurations for IPH

Temp. Range	Solar Collector Type	HTF of Choice	Applications/Comments
< 80°C	Flat plate Non-tracking compound parabolic Solar pond	water	Hot water Space heating
80 to 200°C	Parabolic trough Linear Fresnel	water/steam	Hot water or steam for IPH
200 to 300°C	Parabolic trough Linear Fresnel	Mineral oil	Direct heat or steam for IPH Vacuum-jacket receivers become necessary to minimize heat loss
300 to 400°C	Parabolic trough Linear Fresnel	Synthetic oil	Direct heat or steam for IPH
400 to 550°C	Parabolic trough Linear Fresnel	Steam or Molten salt	Electric power
> 550°C	Heliostat/central receiver Parabolic dish	Steam or Molten salt	Electric power

Solar Industrial Process Heat (SIPH) potential in California

Solar Resource in the Southwest

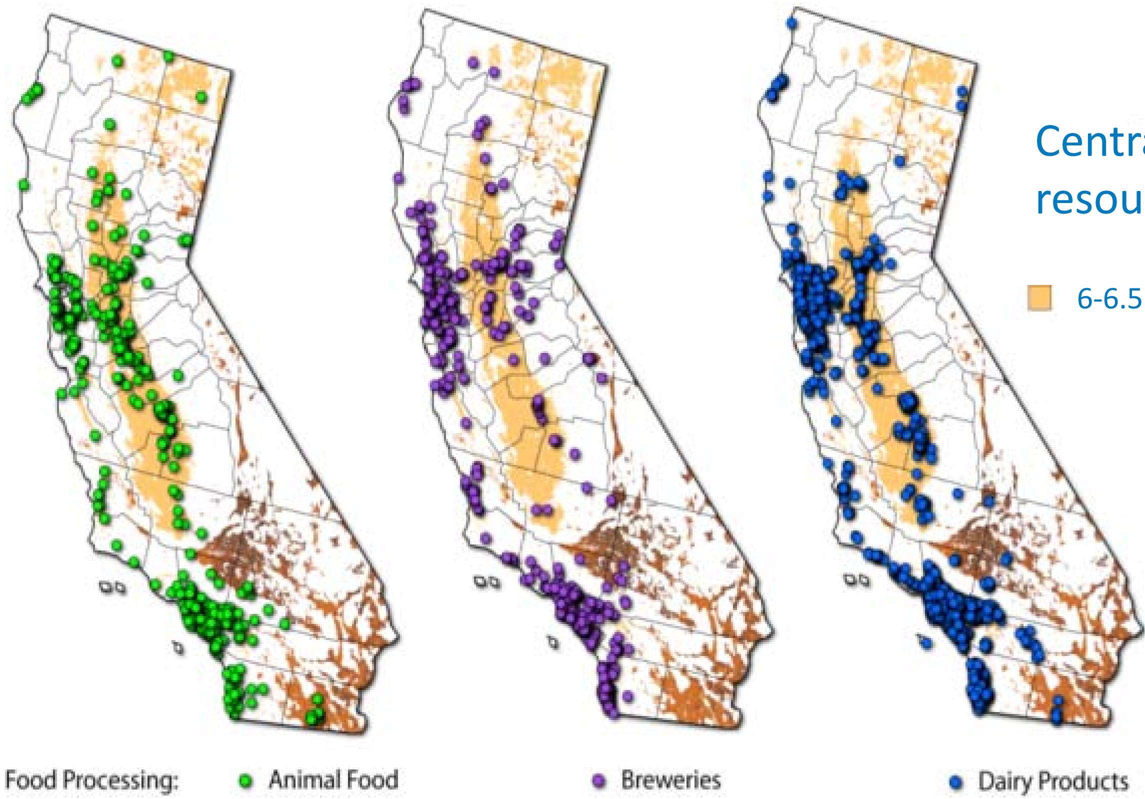


DNI = Direct Normal Irradiance

https://nsrdb.nrel.gov/nsrdb-viewer

Where Potential meets Demand

Technical Thermal Energy Potential of solar with industry locations in California

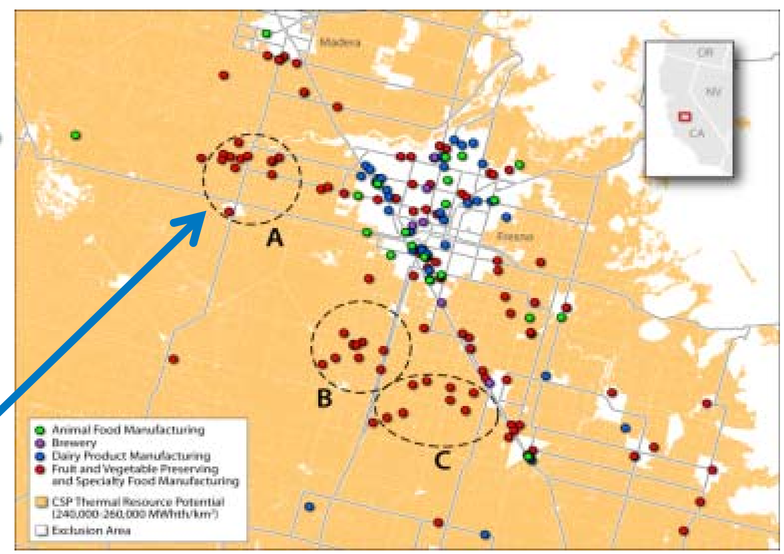


Central Valley provides good resource and industry proximity

6-6.5 kWh/m²/day

Kurup and Turchi, "Initial Investigation into the Potential of CSP Industrial Process Heat for the Southwest United States", NREL, 2015

Fresno, CA example



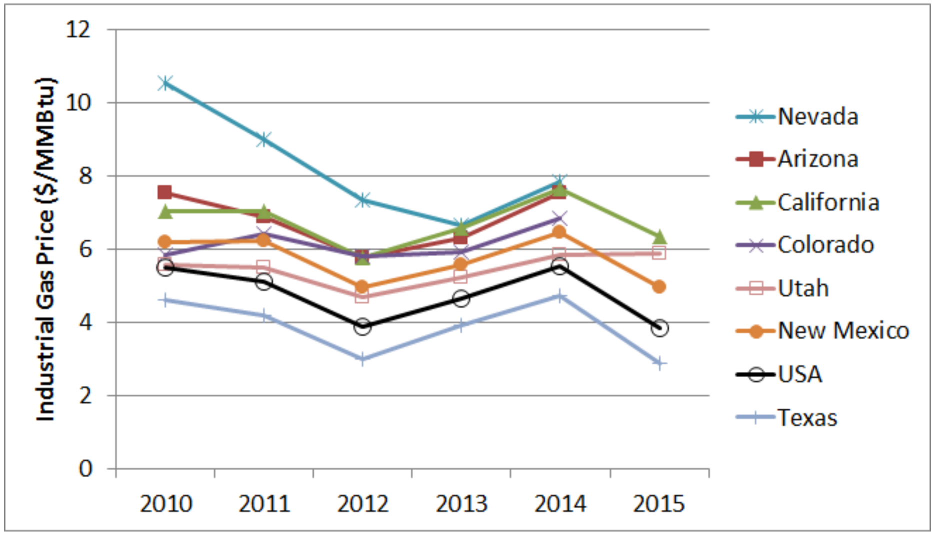
Industries such as Fruit and Veg clustered together in good thermal potential areas

Can SIPH compete with natural gas?

Can CSP IPH compete with Natural Gas?

Gas Trends

- Industrial burner tip prices very different from "Henry Hub"
- Relatively high gas prices in CA make SIPH more attractive



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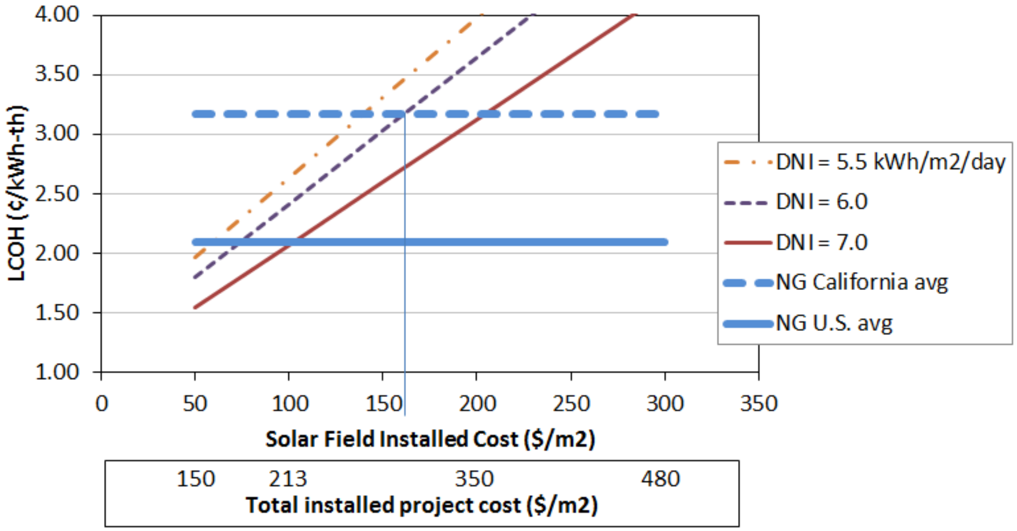
Levelized Cost of Heat (LCOH)

- SIPH competitive with gas in CA at solar field less than $160/m^2$ and DNI > 6.0 $kWh/m^2/day$, or
- Solar field less than $200/m^2$ and DNI > 7.0 $kWh/m^2/day$,



Challenges and Opportunities

Challenges and Caveats

- Solar facilities must achieve these costs at smaller project sizes
- Lower solar field costs are needed to be competitive in key areas of lower DNI (e.g., California's Central Valley)
- Integration of thermal storage (or gas backup) will be required to provide reliability
- Project economics can be very site specific
- Perceived risk impedes deployment

Note: No incentives have been included in this analysis.

Opportunities

- Current incentives for solar process heat
  - Federal Investment tax credit
    - 30% tax credit for solar hardware
  - California Solar Initiative-Thermal
    - \$10.10/therm (\$1/MMBTU, 0.34 ¢/kWh_{th}) of displaced natural gas, up to a maximum of \$800,000
- Niche markets where competition is electric heating or LPG will favor solar

Conclusions

- Industry uses about 22% of total primary energy in the U.S.
  - Of that total, about 1/3 for process heat, with steam at 120 to 220°C commonplace
  - Major industries: Food & Dairy, Paper, Petroleum, Chemicals, and Metals
  - Linear concentrating solar collectors with water/steam or mineral oil are the best configurations in this range
- Price for industrial natural gas prices exceeds utility prices. Prices throughout southwest higher than national average.
- At industrial gas ($6/MMBTU) and solar trough costs ($170/m^2), solar can produce heat for lower cost when DNI > 6.7 kWh/m^2/day. This includes much of the southwest.
- SAM's new SIPH trough model gives accurate simulations

Thank you!

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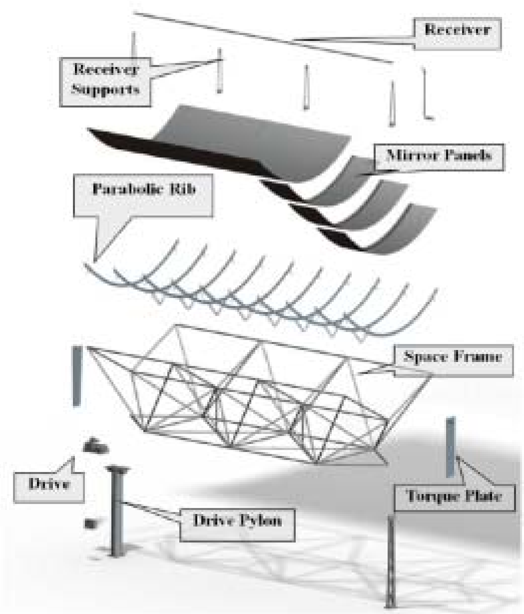
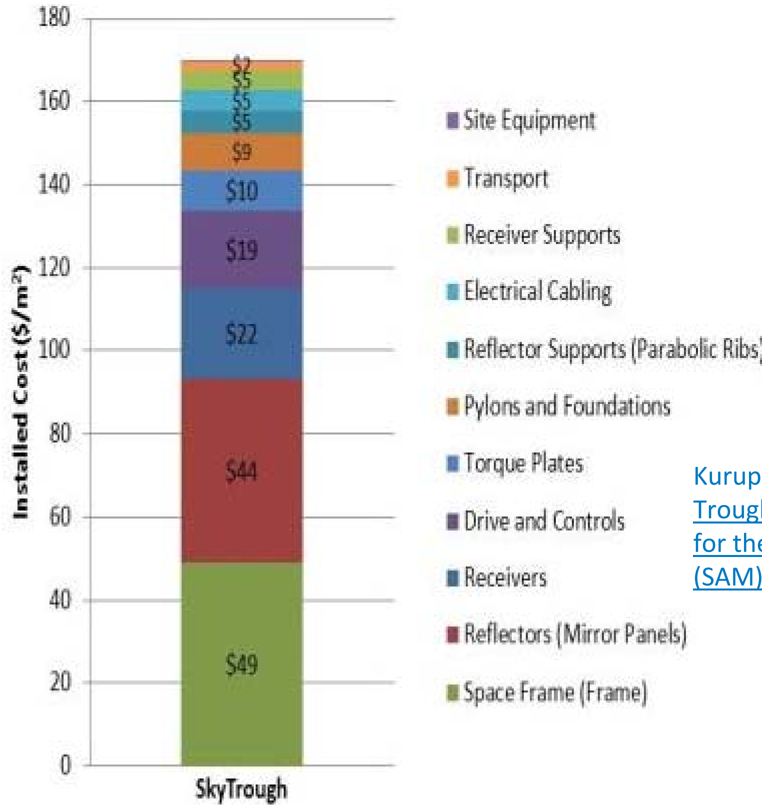
Backup

Current Cost of Parabolic Trough Collectors



SkyTrough Module
8 modules = 1 SCA



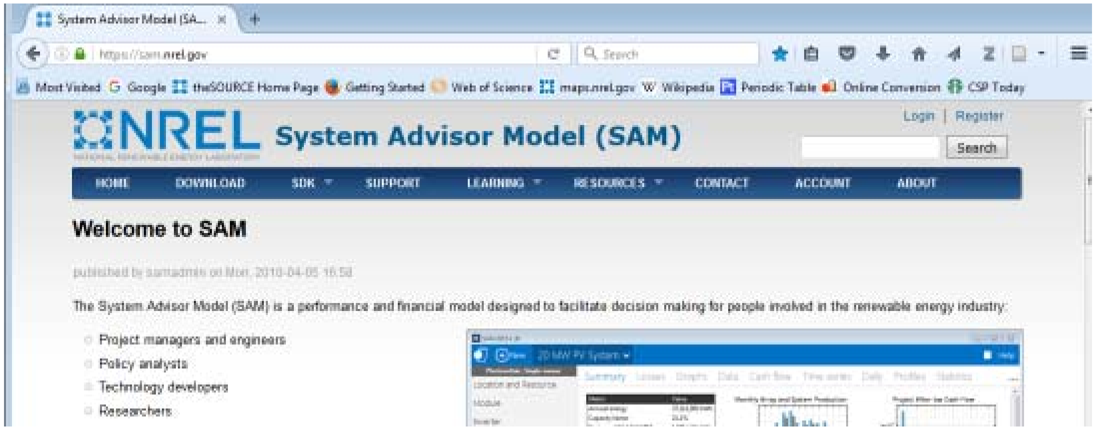
Kurup and Turchi, "Parabolic Trough Collector Cost Update for the System Advisor Model (SAM)", NREL, 2015

- Solar Collector Assembly (SCA) is 115m (Length), Aperture Width 6m
  - ~2.2 SCAs/MW_{th}
- Installed cost for 1500 SCAs = ~\$170/m^2
  - SkyTrough SCAs used at the Stillwater plant
  - Considered suitable for SIPH. Other troughs also suitable e.g. PT1
- Central manufacturing facility for 1500 SCAs/yr for both SIPH and CSP electricity applications
  - Site assembly of Solar Field based on project. Single manufacturing location
  - ~11 SCAs for ~5MW_{th} Solar Field

Modifications to SAM to facilitate IPH

- **System Advisor Model (SAM) was developed to model electric power generation systems**
- **Changes needed to optimize for thermal energy production:**
  - o Remove power cycle constraints
  - o Modify controller/solver for fluid recirculation in absence of power cycle
  - o Allow for smaller scale installations
  - o Clean up and harmonize legacy codes

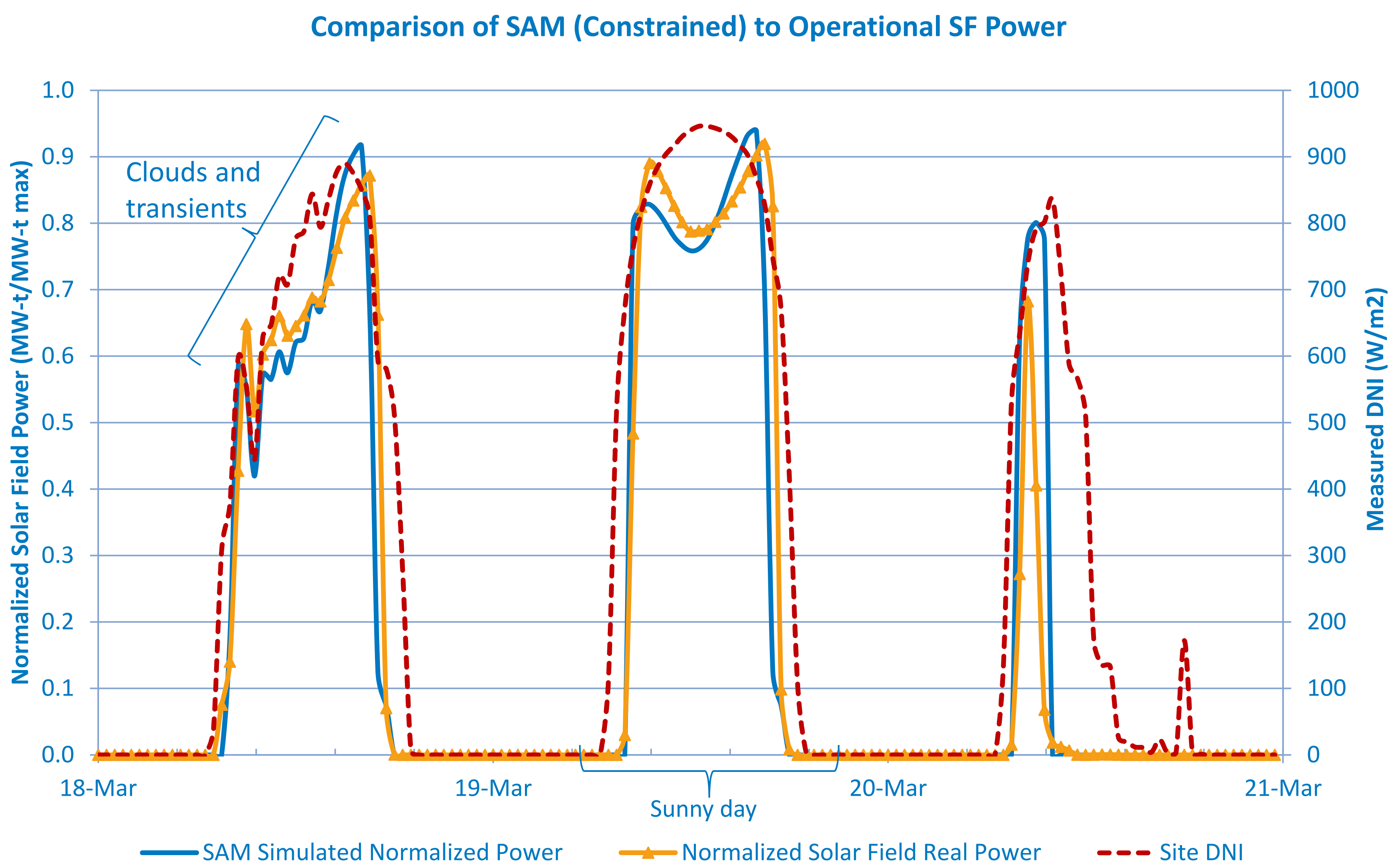
https://sam.nrel.gov/



SAM Thermal Application Models

Model Development Step	Liquid-HTF Trough	Steam Fresnel	Steam Trough
(1) Convert and validate C++ model controller code at single timesteps	✓	✓	✓
(2) Develop TCS shell for system-level validation	✓	✓	✓
(3) Test and debug control modes: off, startup, on, defocus	✓	In progress	In progress
(4) Validate with field data	✓	Data needed	Data needed
(5) Update SAM user interface	In progress		

SAM Simulation Vs. Real Operations



SAM Model Validation compared to Site

The simulation of 58 days of plant data indicate good agreement with the data (project target was within 10%), although there is room for improvement.

Solar field thermal energy output over 58 days (MWh_{th})	SAM thermal energy output, no constraints (MWh_{th})	SAM thermal energy output, constrained* (MWh_{th})
4,832	4,919	4,768
SAM to Site	+1.8%	-1.3%

* SAM not allowed to operate if site solar field power output is < 0 MW_{th}.