Opportunities for Solar Industrial Process Heat in the United States

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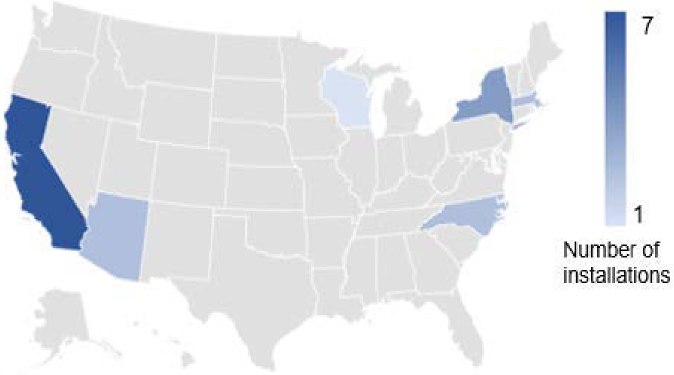
Agenda

1. Analysis framing	Colin McMillan, NREL
2. Industrial process heat (IPH)	Jingyi Zhang, Northwestern University
3. Solar generation	Parthiv Kurup, NREL
4. Opportunities for solar for IPH	Carrie Schoeneberger, Northwestern University
5. Conclusions and future research	Colin McMillan, NREL
6. Q&A	Robert Margolis, NREL Eric Masanet, Northwestern University/UC Santa Barbara William Xi, NREL

Analysis Framing

Analysis Introduction

- Industrial process heat (IPH) is the transfer of heat to a material within a production process by convection, conduction, or radiation
- The potential to use of solar technologies (solar thermal and PV) for meeting IPH in the United States is an understudied and important topic
- The motivating research questions are:
  1. What are the geographic, temporal, and operational characteristics of IPH demand in the United States?
  2. What is the county-by-county **opportunity** to meet IPH demand with solar technologies?



Solar Process Heat Installations (2019)

Adapted from Schoeneberger et al. (2020)

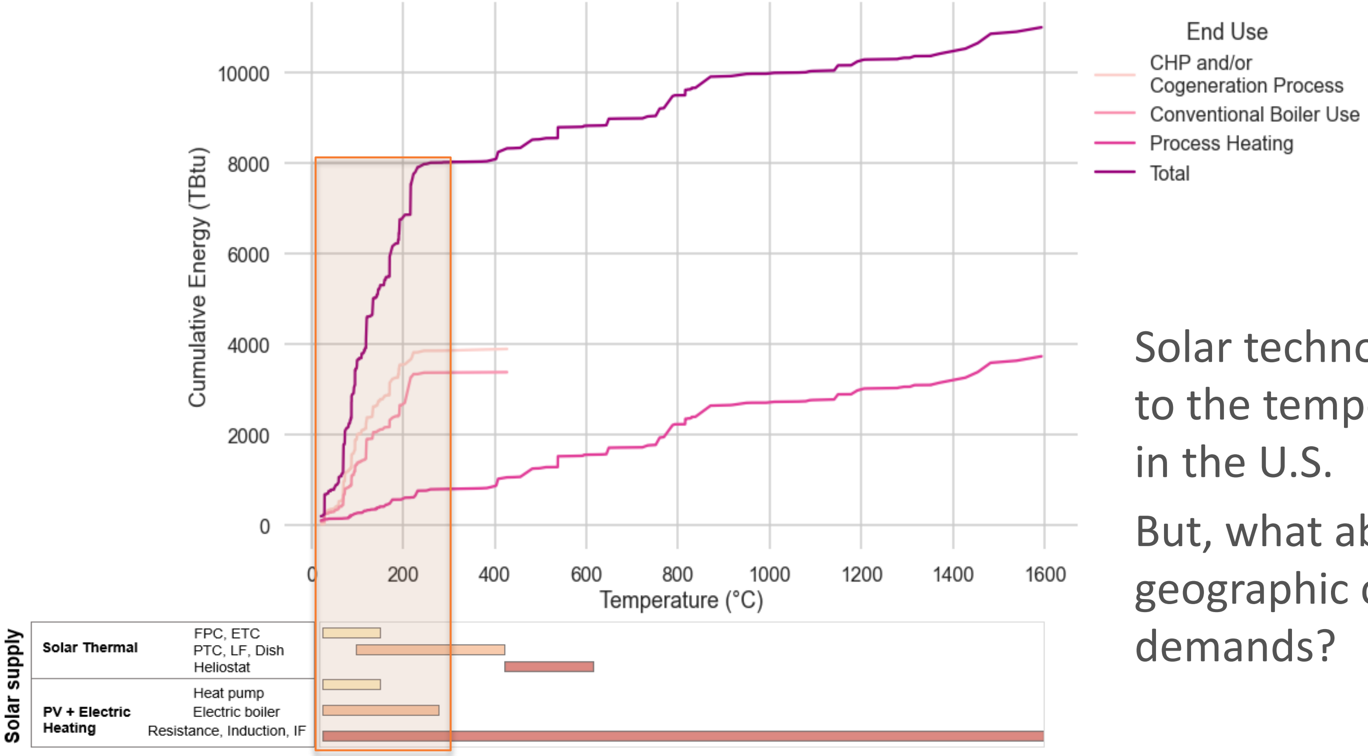
Why Industrial Process Heat (IPH)?

- IPH is a major use of energy in the United States
  - Industry is second-largest user of energy, behind transportation sector
  - IPH is the majority of fuel energy use by industry, equivalent to ~40% of transportation sector and ~28% of residential and commercial buildings combined
- Nearly all IPH energy is provided by fuel combustion
  - Mostly fossil fuels

U.S. DOE. "Manufacturing Energy and Carbon Footprints (2014 MECS)," 2018. https://www.energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2014-mecs.
EIA. "Monthly Energy Review." Energy consumption by sector, 2018. http://www.eia.gov/totalenergy/data/monthly/#consumption.

Why Solar for IPH?

U.S. Cumulative IPH Demand by Temperature in 2014

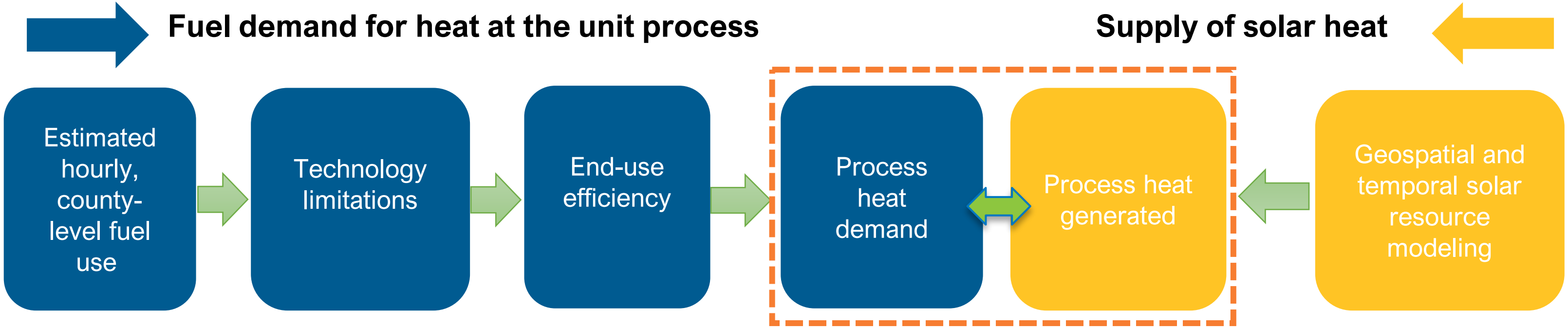


Solar technologies are well-matched to the temperature demands of IPH in the U.S.

But, what about temporal and geographic characteristics of IPH demands?

Adapted from Schoeneberger et al. (2020)

Analysis Framework and Approach



Fuel demand for heat at the unit process

Supply of solar heat

Estimated hourly, county-level fuel use

Technology limitations

End-use efficiency

Process heat demand

Process heat generated

Geospatial and temporal solar resource modeling

Overall approach is to characterize hourly IPH loads and match them with the appropriate hourly supply of solar heat.

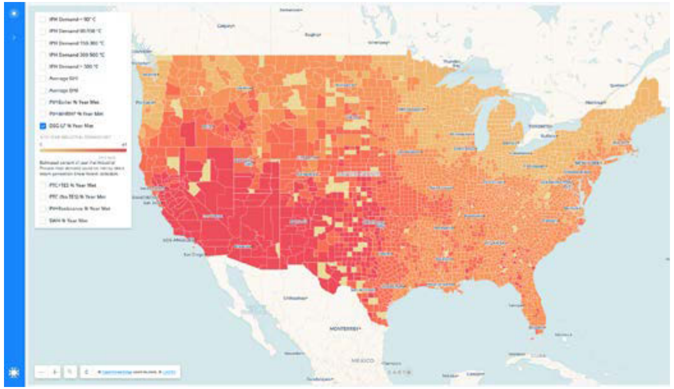
Analysis Scope

Opportunity for SIPH is defined as *the fraction of process heat demand that can be provided by solar technologies, given available solar resources and land area*

Includes	Excludes
✓ County-average solar resource ✓ County total land availability ✓ IPH unit process detail, including temperature, heat media, and boiler type ✓ Hourly heat load and solar generation ✓ Uncertainty ranges of typical operating schedules	☒ Site-level analysis ☒ Economic considerations ☒ Battery storage ☒ Multiple varieties of a single solar technology type ☒ Emerging solar technologies ☒ Hawaii, Alaska, and Puerto Rico

Analysis Contributions

- Analysis is a first, key step to exploring how solar IPH technologies could be relevant for U.S. industries
- Expand solar for IPH to include PV-connected electrotechnologies
- Results are useful at the national, state, and local levels
- Publicly-available resources for continued analysis
  - Data sets on IPH characterization, load shapes
  - Interactive results viewer
  - Open-source code



https://www.nrel.gov/analysis/solar-industrial-process-heat.html

Industrial Process Heat

IPH Data Disaggregation

IPH Characteristic	**Existing Detail**	**New Disaggregation**
Geographic	County (NREL), Census Region (EIA MECS)	County
Temporal	Annual	**Hourly**
Operational – Temperature	None	**Process temperature**
Operational – Process	General end use (e.g., conventional boiler, process heating)	**General end use with equipment efficiencies and capacities**

Matching Solar Technologies with IPH Applications

7 solar "technology packages"

Conventional IPH Technologies and Applications	Solar Technologies		
Conventional boiler, CHP; hot water (<90°C)	Flat plate collector (w/ water storage)		(1)
Conventional boiler, CHP, process heat	Parabolic trough collector (w/wo 6-hr thermal energy storage)		(2)
	Linear Fresnel, direct steam generation		(3)
Conventional boiler, CHP; hot water (<90°C)	Ambient heat pump (HP) (w/ water storage)	PV	(4)
Conventional boiler (steam and hot water)	Electric boiler		(5)
Conventional boiler, CHP, process heat	Resistance heater		(6)
Conventional boiler, CHP, process heat	Waste heat recovery HP (WPRHP)		(7)

Conventional IPH technology and application

IPH electrotechnology

Solar technology

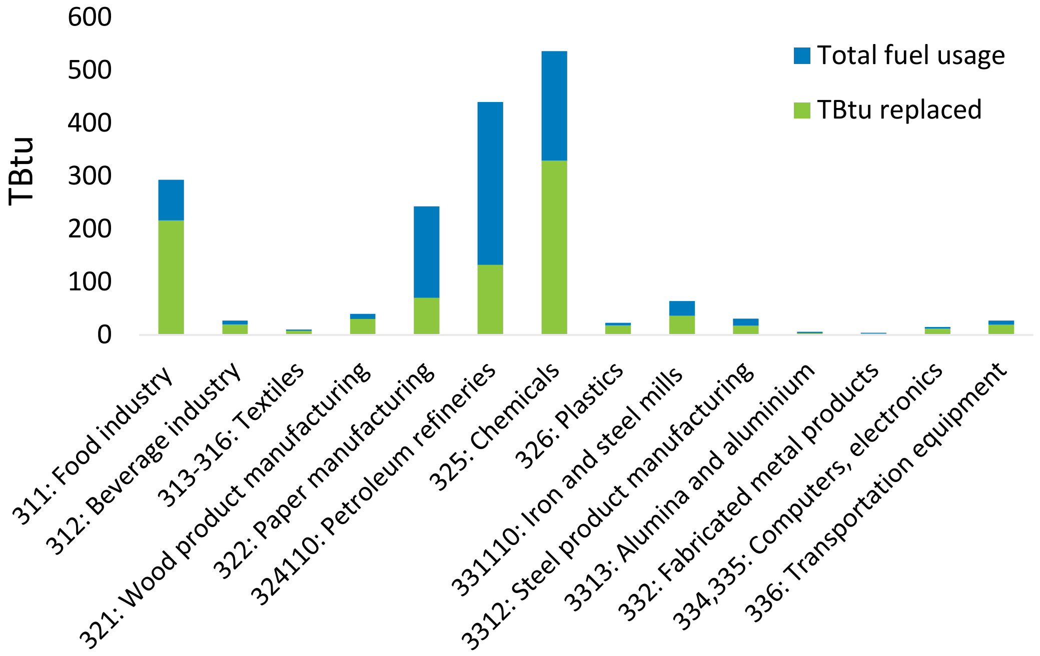
Process Heat Technologies: Electrotechnologies

- In addition to modeling boilers and CHP, electrotechnologies were selected based on criteria for technical potential
  - PV+ [ambient HP, electric boiler, resistance heating, and waste heat recovery HP (WHRHP)]
  - Selection based on weighted scoring of technical potential to replace conventional technologies, data sufficiency, and market growth potential

Electrotechnology Screening

Electrotechnologies	Technical Potential for Conventional Fuel Replacement	Weighted Score of Technical Potential	Data Availability	Weighted Score of Modeling Confidence	Market Growth Outlook	Weighted Score of Market Growth Outlook	Overall Score
Electric boiler	3	6	3	3	3	3	**12**
Ambient heat pump	3	6	3	3	2	2	**11**
Resistance heating and melting	3	6	3	3	2	2	**11**
Waste recovery heat pumps	2	4	3	3	3	3	**10**
Induction heating and melting	2	4	3	3	3	3	10
Infrared processing	2	4	3	3	3	3	10
Microwave heating and drying	2	4	3	3	3	3	10
Radio-frequency heating and drying	2	4	3	3	3	3	10
Direct arc melting	2	2	3	3	3	3	10
UV (ultraviolet) curing	1	2	3	3	3	3	8
Plasma processing	1	2	3	3	2	2	7
Vacuum melting	1	2	2	2	3	3	7
Laser processing	1	2	3	3	2	2	7
Ladle refining	1	2	1	1	1	1	4

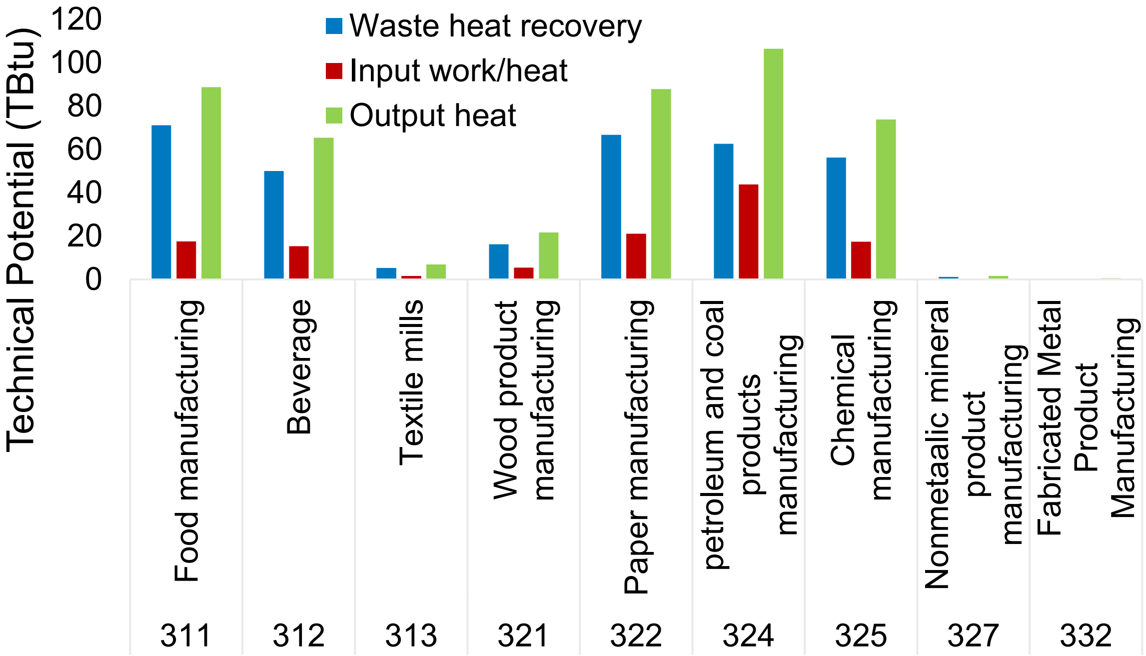
Technical Potential of Replacing Conventional Boilers with e-Boilers



2014 conventional boiler fuel use (TBtu/yr)	Fossil fuel	827
	Fossil fuel	827
	Other fuel	932
	Total	1759
Technical potential	Boiler fuel replacement	52%
	TBtu replacement	916

The result assumes single boiler replacement with a maximum e-boiler capacity of 190 MMBtu/hr

Technical potential of waste heat recovery heat pumps (WHRHPs)



	Total
Input work/heat (TWh)	3.60E+01
Waste heat recovery (TBtu)	3.30E+02
Output heat (TBtu)	4.53E+02

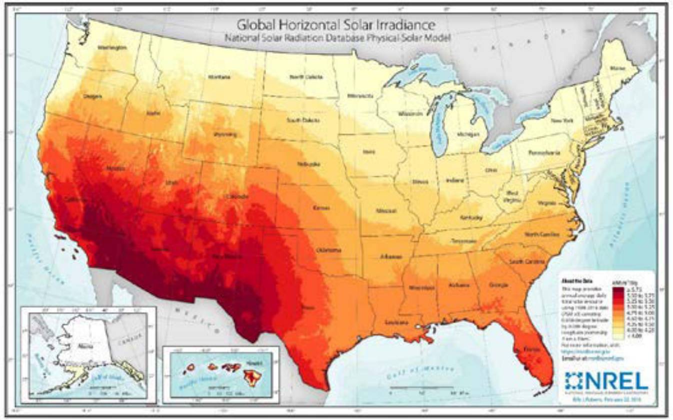
Waste heat recovery = Input fuel × waste heat fraction × waste heat not recovered

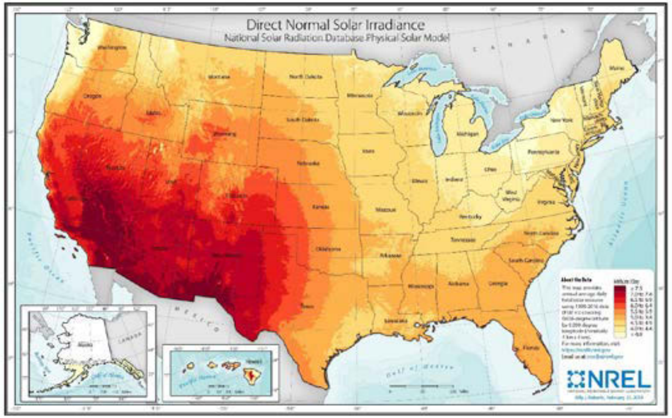
Output heat = Input work or heat × COP -> Input work or heat = waste heat recovery/(COP-1)

Solar Generation

Solar Resource and Land

- Significant solar resource across the US:
  - GHI: Range is 1,000 – 2,500 kWh/m2/year
  - DNI: Range is 1,450 – 2,740 kWh/m2/year
- Solar IPH suitability across the US
  - Huge potential for PV for heat
  - For CSP, Southwest, but also across the country due to decreased resource need compared to electricity
- Land availability for SIPH typically in each state is greater than the land needed to meet all the state's demands
  - Modelling using new exclusion criteria





Solar Technology Packages and Applications

Conventional IPH Technologies and Applications	Solar Technologies		
Conventional boiler, CHP; hot water (<90°C)	Flat plate collector (w/ water storage)		**(1)**
Conventional boiler, CHP, process heat	Parabolic trough collector (w/wo 6-hr thermal energy storage)		**(2)**
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Conventional boiler, CHP; hot water (<90°C)	Ambient heat pump (HP) (w/ water storage)	PV	(4)
Conventional boiler (steam and hot water)	Electric boiler		(5)
Conventional boiler, CHP, process heat	Resistance heater		(6)
Conventional boiler, CHP, process heat	Waste heat recovery HP (WPRHP)		(7)

Solar thermal technologies (**1-3**) are commercial for low (e.g., <90°C) and medium temperatures (e.g., 100-300° C)

PV-connected heat technologies (**4-7**) are still early stage
- AC based: HP and WHRHP
- DC based: eBoiler and Resistance heater (90-1,800°C)

Conventional IPH technology and application

IPH electrotechnology

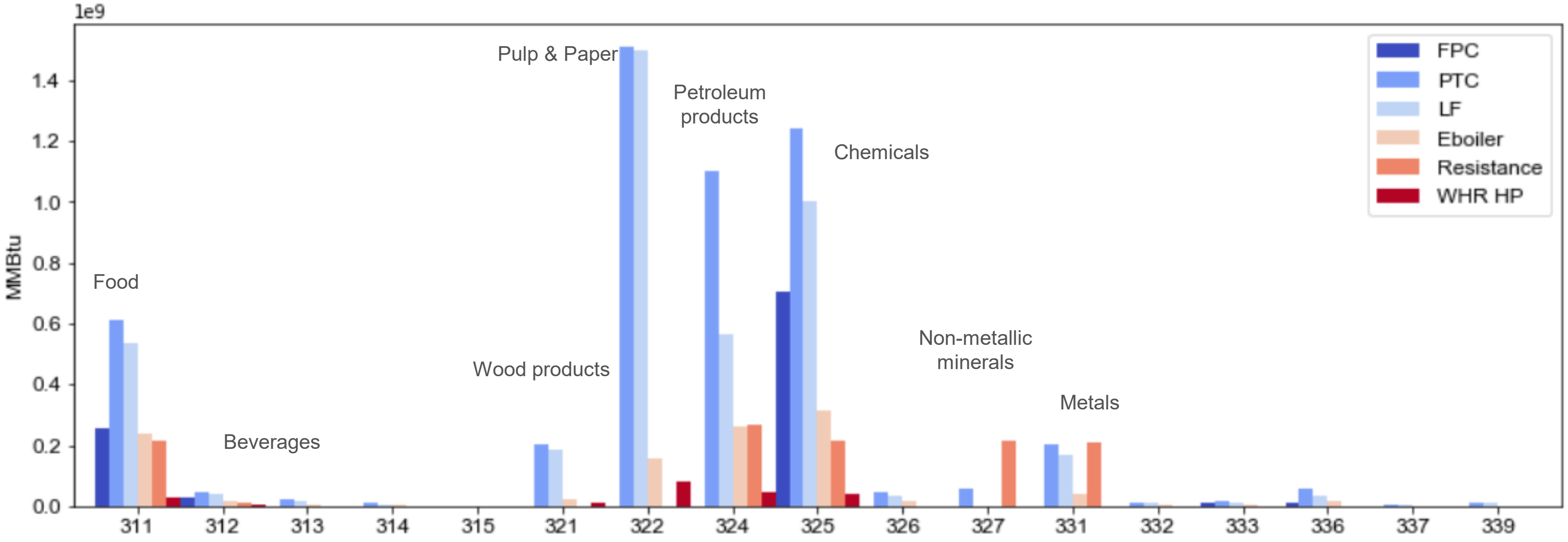
Solar technology

Modelling

- NREL’s System Advisor Model (SAM), 2020.11.29
  - Technology parameters defined for the technology package
- NREL’s Renewable Energy Potential (reV) Model used to estimate generation by county
  - Detailed spatiotemporal modeling assessment tool that calculates renewable energy capacity, generation, and cost based on geospatial intersection with grid infrastructure and land-use characteristics.
  - Technology package from SAM run on reV, via high performance computing, for every county e.g., ~3000 times
- PV and Heat Pump
  - Models developed by Stephen Meyers
  - Hourly PV-generated electricity (from SAM output and reV JSON) is used to power a heat pump that “lifts” heat from ambient air into water that is stored and subsequently used to heat a process load at its desired temperature

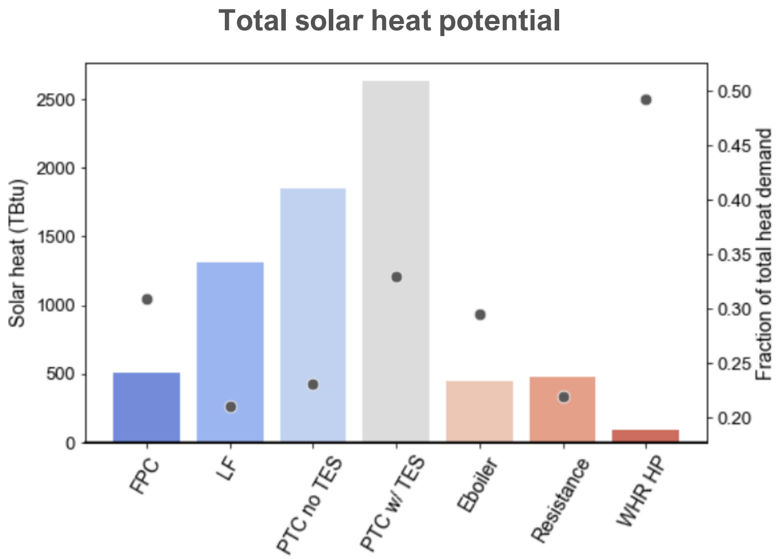
Opportunities for SIPH

Process-level Heat Demand by Industrial Subsector



- Shows how much process-level heat demand each technology could theoretically meet within a given subsector
- Highest potential demand in pulp & paper, chemicals, petroleum, and food

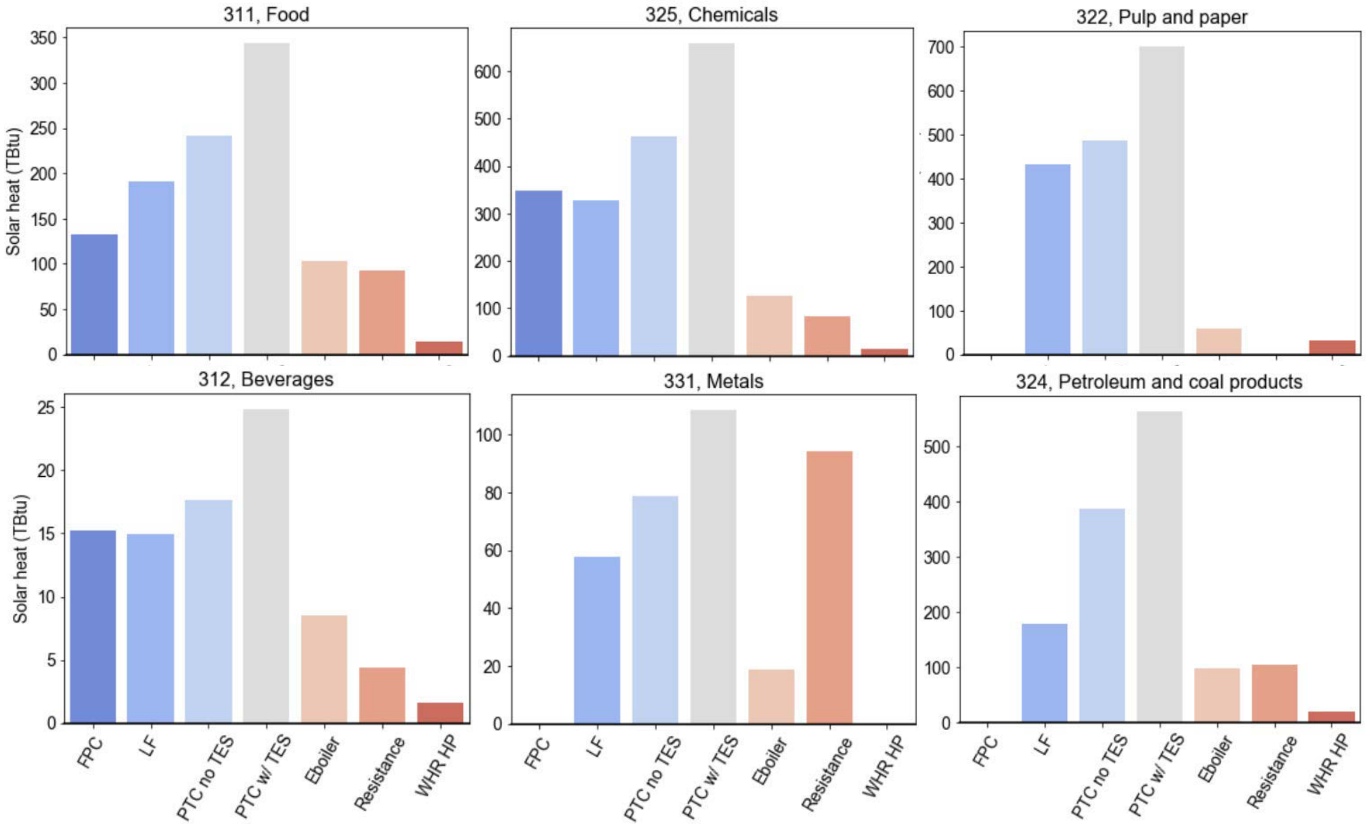
Opportunities for SIPH by Technology



- in TBtu (bars)
- as the fraction of total IPH demand calculated for the technology (dots)

- Based on hourly calculations of solar fractions
- Shows total annual heat potential by solar technology in TBtu and as a fraction of total IPH demand for the technology
- Overall, highest solar heat potential with concentrating collector technologies

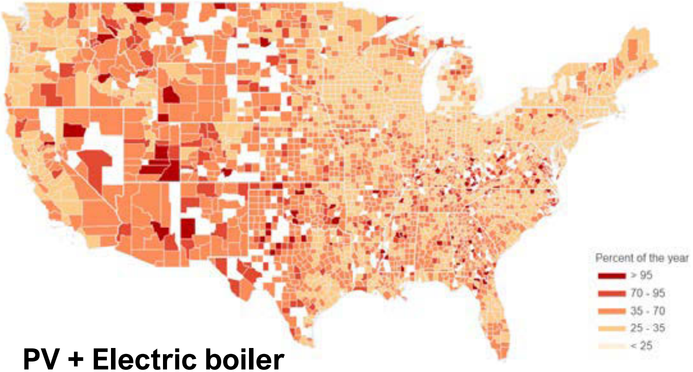
Solar Heat Potential by Industrial Subsector



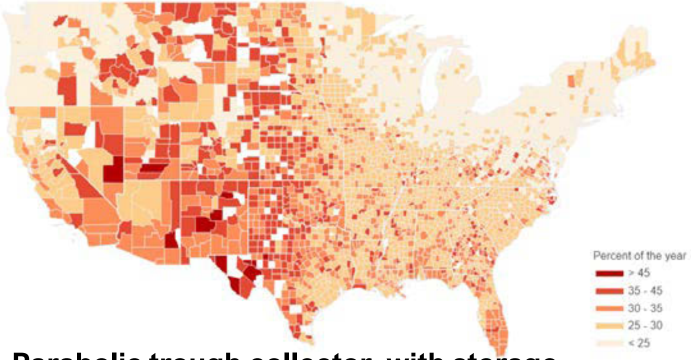
- Shows total annual solar heat potential within a few subsectors
- In subsectors with medium temp. steam needs, concentrating collectors have high potentials
- In metals, electric resistance heating has high potential

Frequency of Solar Heat Fully Meeting Process Heat Demand

Flat plate collector, with storage

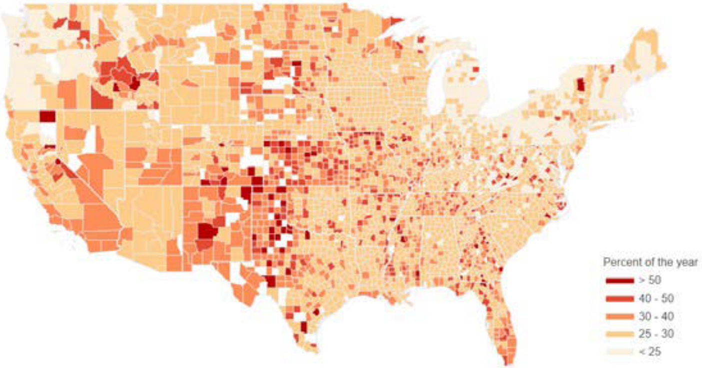


Parabolic trough collector, no storage

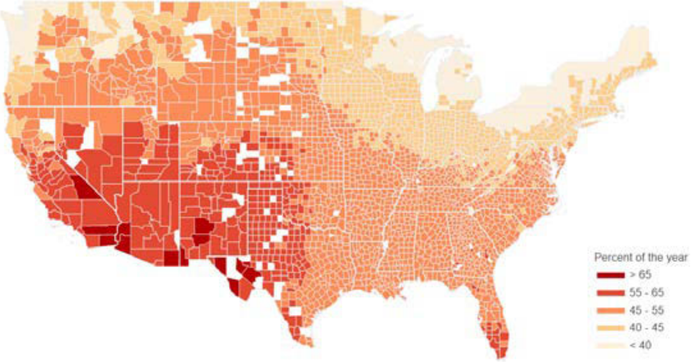


Note: color bins are different per technology

PV + Electric boiler



Parabolic trough collector, with storage

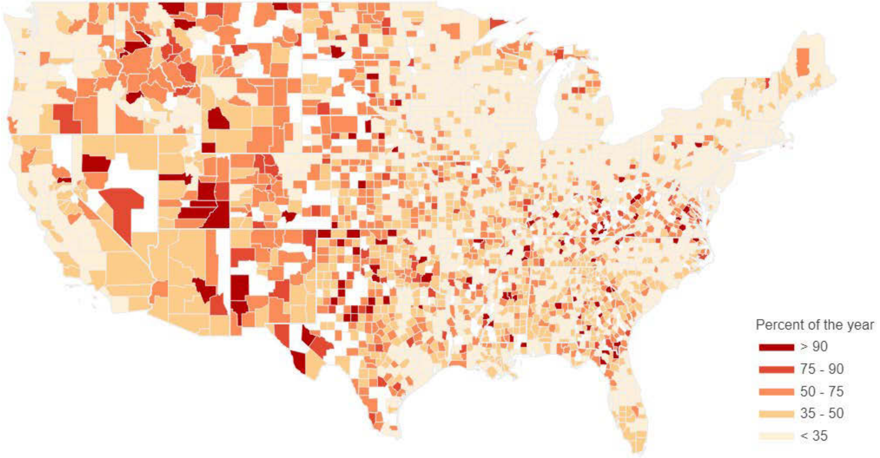


- Based on hourly solar fraction: when the solar fraction is 1 or greater, solar heat can fully meet demand
- Maps show how often during the year that solar heat is fully meeting demand in the county

Comparison of Summer and Winter Sizing

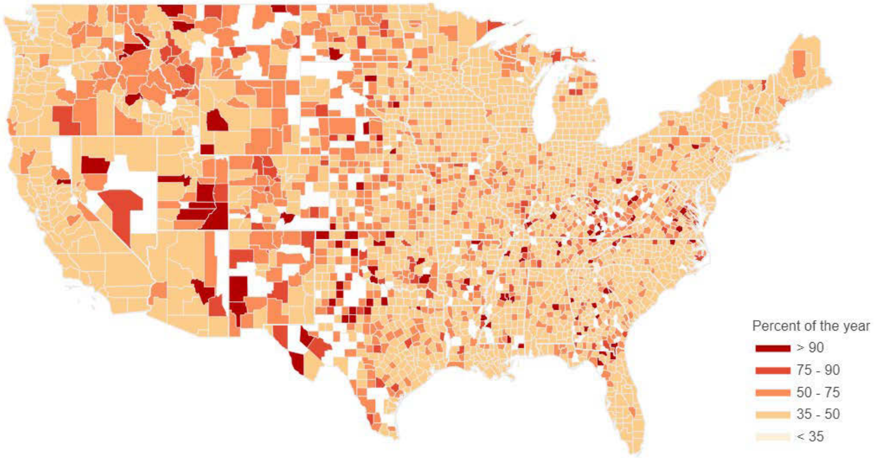
Summer sizing

Flat plate collector, with storage



Winter sizing

Flat plate collector, with storage

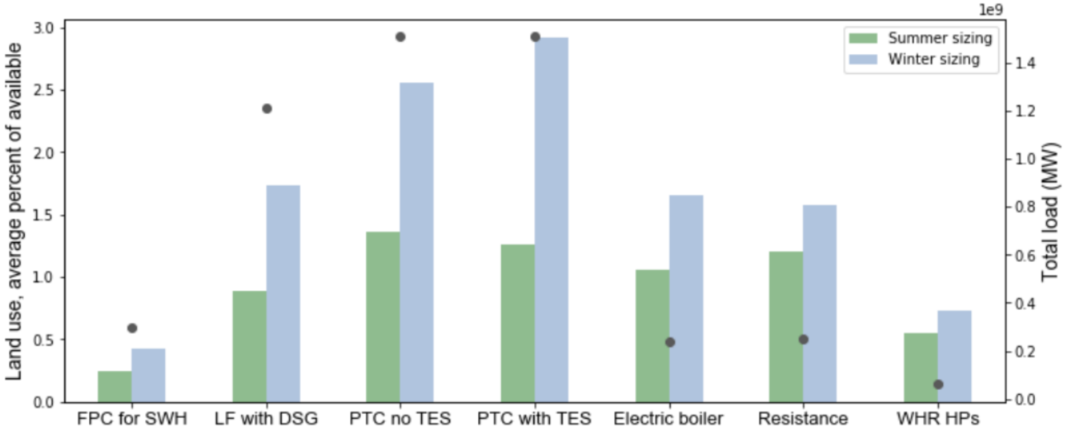


- To compare the effect of solar system sizing, solar systems were scaled to meet peak load by county in summer (June) and winter (December)
- With winter sizing, solar technologies can meet heat demand more often

SWH = solar water heating; DSG = direct steam generation

Land Use Requirements

Land use as percentage of available land (bars) & Total load in MW (dots)



- Land use is dependent on total heat load since solar systems were scaled to meet peak load
- More land required for PV electric heating systems

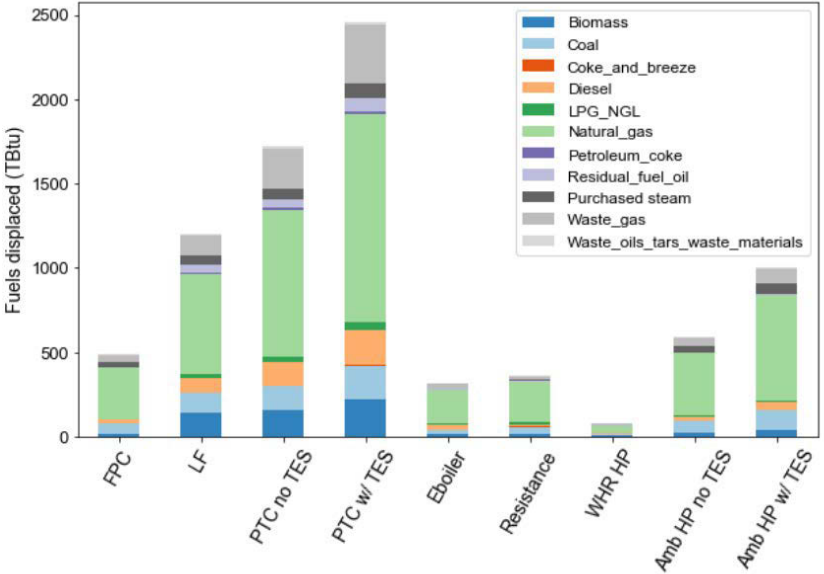
Land use, totals in km²

As a comparison, Connecticut, the third smallest state by area, is 14,357 km²

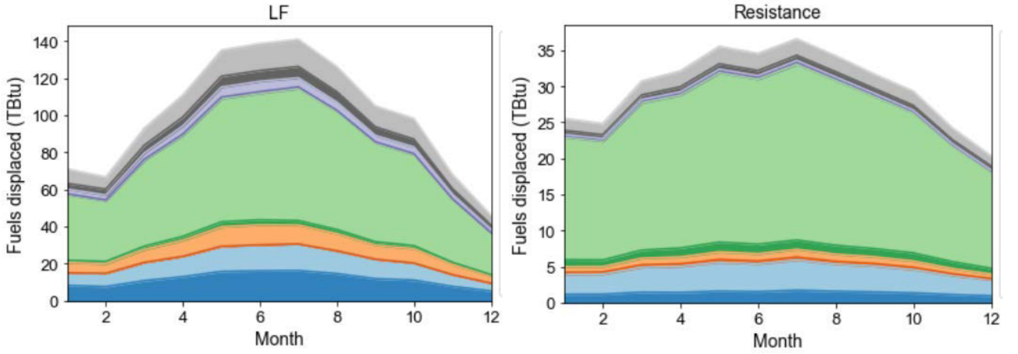
	FPC	LF DSG	PTC no TES	PTC w/ TES	E-boiler	Resistance	WHR HPs
Summer sizing	221	2,711	4,515	5,463	3,875	4,958	1,130
Winter sizing	521	7,385	14,620	18,960	6,533	8,127	1,911

Fuel Savings

Total annual fuels displaced

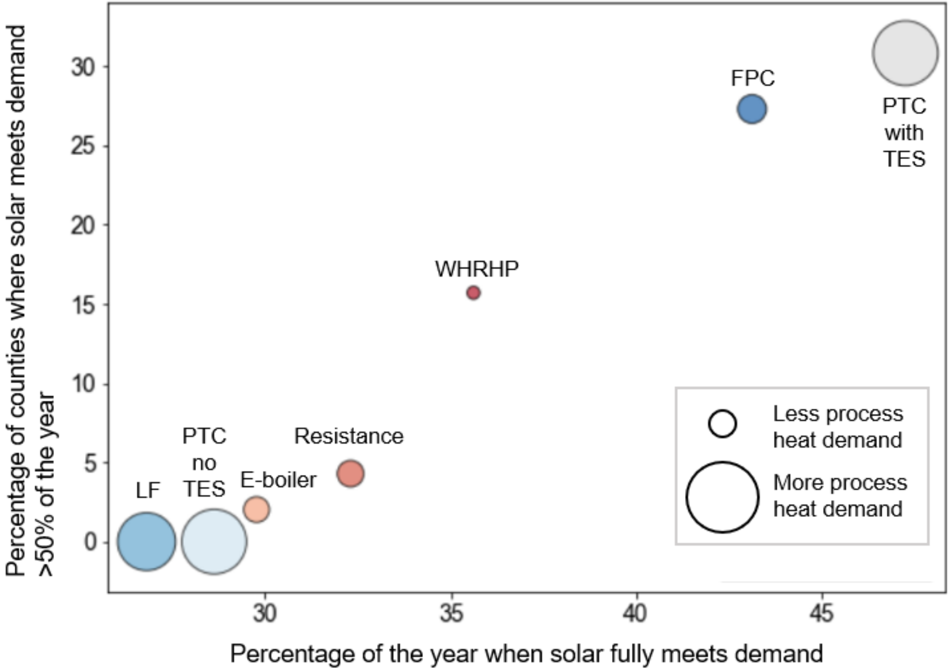


Monthly total fuels displaced for LF and PV + Resistance heating



- Amount of fuels displaced for each technology mirrors solar heat potential, with concentrating technologies highest
- Fuels displaced increases in summer months and varies by fuel types for a technology

Summary Comparison of Technologies



- Shows how often during the year a technology fully meets heat demand and for how many counties where it can meet heat demand at least half the year
- Solar systems with thermal energy storage (PTC with TES and FPC) meet demand most often and for the most counties

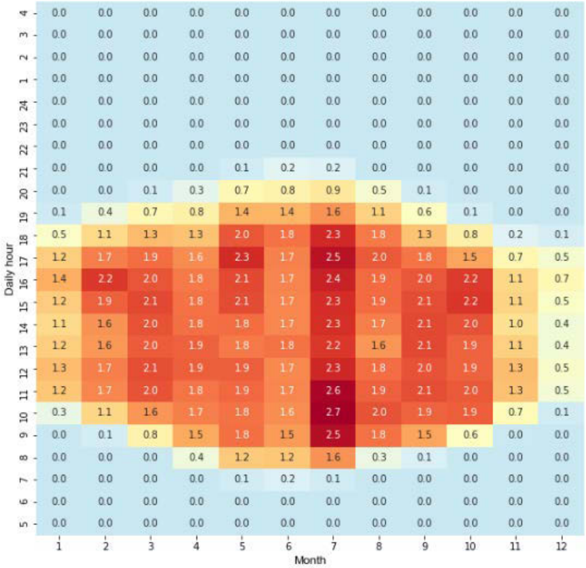
Conclusions and Future Research

Conclusions

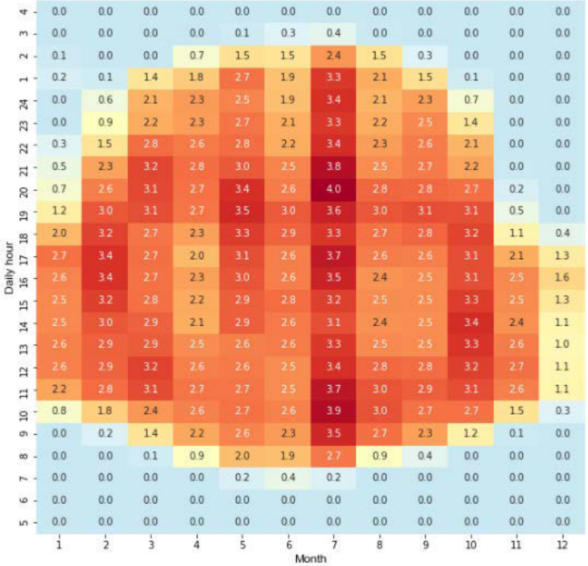
- First national level analysis for the U.S., conducted at the county level
- Solar thermal and PV heat technologies can meet many temperature needs; nearly 25% of 2014 IPH demand
- Most counties have sufficient available land, although site-specific details matter
  - On average only 5% of land is needed
  - However, site assessment for individual facilities is needed to determine economic viability

- **Key insight:** All CONUS states can readily benefit from solar heat technologies, and meet a large portion of their IPH demand
- **Key insight:** possible for heating technologies to reduce CO_2 emissions by ~15%
- **Key insight:** thermal energy storage is a key for solar IPH success

Importance of Thermal Energy Storage (TES)



Parabolic trough collector, no storage



Parabolic trough collector, with storage

- Comparison of hourly solar fraction, averaged for the month, between PTC with and without TES for Polk County, Iowa
- Large, energy-intensive industries tend to run continuously
- TES extends the hours when solar fully meets demand, leading to more fuel savings and emissions reductions

Future Research

Just the start and more research is needed!

- Higher resolution analysis
  - Location-specific modeling to match the supply and demand e.g., 500m to the site, land available, heat transport, specific site load demands and integration
- Increased options for energy storage
  - Thermal batteries e.g., grid tied to pull low-cost renewable electricity
  - Electric batteries to couple with the PV-based systems
- Increased integration efforts for viability
  - Unlike electricity, heat is not as fungible, and needs proper integration
- Facility decision support
  - Solar heat supply side considerations (e.g., different technologies) coupled to the user inputs e.g., load, natural gas use and land

Thank you!

Q&A

www.nrel.gov

McMillan, Colin, Carrie Schoeneberger, Jingyi Zhang, Parthiv Kurup, Eric Masanet, Robert Margolis, Steven Meyers, Mike Bannister, Evan Rosenlieb, and William Xi. 2021.*Opportunities for Solar Industrial Process Heat in the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-77760.

https://www.nrel.gov/docs/fy21osti/77760.pdf

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Backup

Solar Supply

Process Heat Technologies

Solar technology	Characteristics	Applicable end use	Limited to
FPC	Temperature, 90°C Uses: hot water, boiler feedwater preheating	Conventional boiler, CHP	Hot water only
CSP	Temperature, 400°C Uses: steam, direct proc. heat	Conventional boiler, CHP, PH	Process temp <340°C
PV + HP (ambient)	Temperature, <90°C Uses: hot water	Conventional boiler	Hot water only
PV + electric boiler	Uses: steam, hot water	Conventional boiler	Capacity<50MW
PV + resistance	Temperature, 1800°C Uses: furnaces, ovens, kilns	*PH, Conventional boiler, CHP*	Process temp <1800°C, relevant unit processes and industries
PV + HP (waste heat)	Temperature, 160°C Uses: steam, hot water, hot air	Conventional Boiler, CHP, PH	Relevant unit processes and industries

Land Exclusion Criteria

Data Set	Criteria
Slope	Slopes greater than 3% (for parabolic trough) or 5% (for PV or FPC)
Urban Areas	Suburban areas
	Urban areas
Land Cover	Open water
	Woody wetlands
	Emergent herbaceous wetlands
	Deciduous forest
	Evergreen forest
	Mixed forest
BLM ACEC	Bureau of Land Management areas of critical environmental concern
Federal Lands	National battlefield
	National conservation area
	National fish hatchery
	National monument
	National park
	National recreation area
	National scenic area
	National wilderness area
	National wildlife refuge
	Wild and scenic river
	Wildlife management area
	National forest

Data Set	Criteria
Federal Lands (cont.)	National grassland
	U.S. Air Force Guard land
	U.S. Air Force land
	U.S. Army land
	U.S. Army Guard land
	U.S. Coast Guard land
	U.S. Marine Corps land
	U.S. Navy land
	Mixed forest
Airports	Airports
Protected Areas Database of the United States	Status 1: an area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events (of natural type, frequency, intensity, and legacy) are allowed to proceed without interference or are mimicked through management
	Status 2: an area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance.
National Conservation Easement Database	Status 1: managed for biodiversity: disturbance events proceed or are mimicked
	Status 2: managed for biodiversity: disturbance events suppressed

Solar Technology Packages

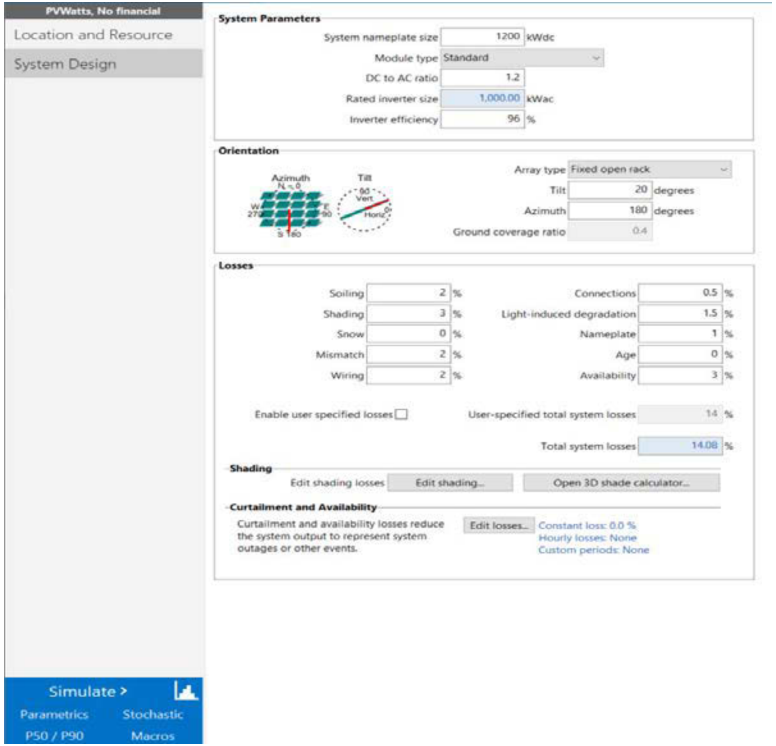
Technology Package	MW_{th} of Solar Field	MW_{th} at the Heat Exchanger	HTF	Volume of TES/Hours of Storage	Collector/Type	Total Land Area	Aperture Area/ Absorption Area (m^2)
Solar water heating-FPC	1.0	~1.27	Glycol	60 m^3	Heliodyne Gobi 410 001	~0.5 acres	2,014 m^2
CSP: oil trough, no TES	1.5	1.00	Therminol-VP-1	0	SkyFuel SkyTrough	~2 acres/ ~8,094 m^2	2,624 m^2
CSP: oil trough, 6 hours of TES	2.5	1.00	Therminol-VP-1	6 hours	SkyFuel SkyTrough	~4 acres/ ~16,187 m^2	5,248 m^2
CSP with DSG LF collector, no TES	1.2	1.00	Water/Steam mix	0	Novatec	~1 acre/ ~3,698 m^2	3,082 m^2
PV DC for connection to resistive heater and eBoiler	1.2	NA	NA	NA	Standard module from PVWATTs Calculator with fixed open rack	In SAM output	In SAM output

For PV AC, the same solar field is used, but 1 MWe is used as the system size. DC : AC inverter ratio = 1.2

Defined as ~1 MW systems; scaled by sizing to winter peak and summer peak, system footprint, and available land area

SAM Technology Parameters Examples

Indirect Heating - Direct Steam Generation Linear Fresnel Collectors



PVWatts, No financial

System Parameters

System nameplate size 1200 kWdc
Module type Standard
DC to AC ratio 1.2
Rated inverter size 1,000.00 kWac
Inverter efficiency 96 %

Orientation

Array type Fixed open rack
Tilt 20 degrees
Azimuth 180 degrees
Ground coverage ratio 0.4

Losses

Soiling	2	%	Connections	0.5	%
Shading	3	%	Light-induced degradation	1.5	%
Snow	0	%	Nameplate	1	%
Mismatch	2	%	Age	0	%
Wiring	2	%	Availability	3	%

Enable user specified losses ☐
User-specified total system losses 14 %
Total system losses 14.08 %

Shading

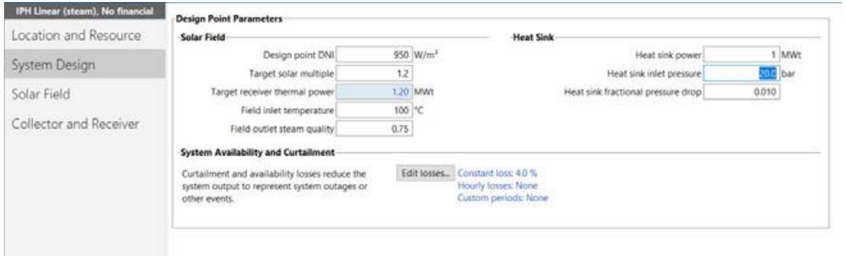
Edit shading losses

Curtailment and Availability

Curtailment and availability losses reduce the system output to represent system outages or other events.

Constant loss: 0.0 %
Hourly losses: None
Custom periods: None

Direct Heating - Direct Steam Generation Linear Fresnel Collectors



IPH Linear (steam), No financial

Design Point Parameters

Solar Field

Design point DNI 950 W/m²
Target solar multiple 1.2
Target receiver thermal power 1.20 MWt
Field inlet temperature 100 °C
Field outlet steam quality 0.75

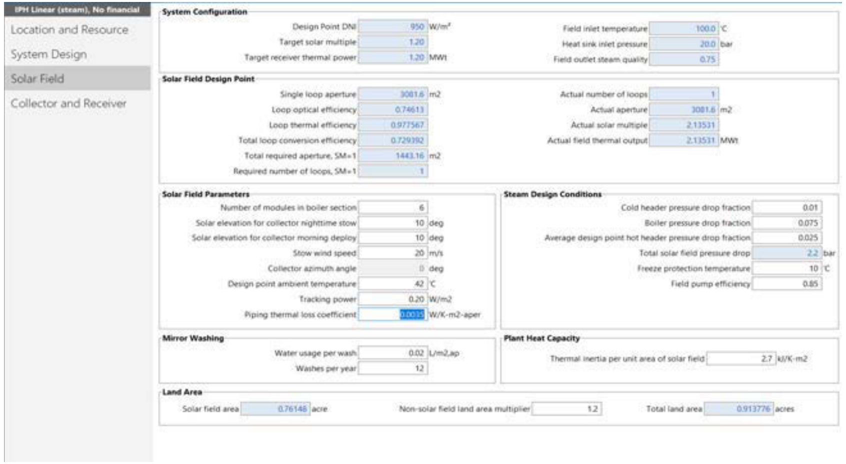
Heat Sink

Heat sink power 1 MWt
Heat sink inlet pressure 20.0 bar
Heat sink fractional pressure drop 0.010

System Availability and Curtailment

Curtailment and availability losses reduce the system output to represent system outages or other events.

Constant loss: 4.0 %
Hourly losses: None
Custom periods: None



IPH Linear (steam), No financial

System Configuration

Design Point DNI 950 W/m²
Target solar multiple 1.20
Target receiver thermal power 1.20 MWt
Field inlet temperature 100.0 °C
Heat sink inlet pressure 20.0 bar
Field outlet steam quality 0.75

Solar Field Design Point

Single loop aperture 3081.6 m2
Loop optical efficiency 0.74613
Loop thermal efficiency 0.977567
Total loop conversion efficiency 0.729392
Total required aperture, SM=1 1443.16 m2
Required number of loops, SM=1 1
Actual number of loops 1
Actual aperture 3081.6 m2
Actual solar multiple 2.13531
Actual field thermal output 2.13531 MWt

Solar Field Parameters

Number of modules in boiler section 6
Solar elevation for collector nighttime stow 10 deg
Solar elevation for collector morning deploy 10 deg
Stow wind speed 20 m/s
Collector azimuth angle 0 deg
Design point ambient temperature 42 °C
Tracking power 0.20 W/m2
Piping thermal loss coefficient 0.0035 W/K-m2-aper

Steam Design Conditions

Cold header pressure drop fraction 0.01
Boiler pressure drop fraction 0.075
Average design point hot header pressure drop fraction 0.025
Total solar field pressure drop 2.2 bar
Freeze protection temperature 10 °C
Field pump efficiency 0.85

Mirror Washing

Water usage per wash 0.02 L/m2,ap
Washes per year 12

Plant Heat Capacity

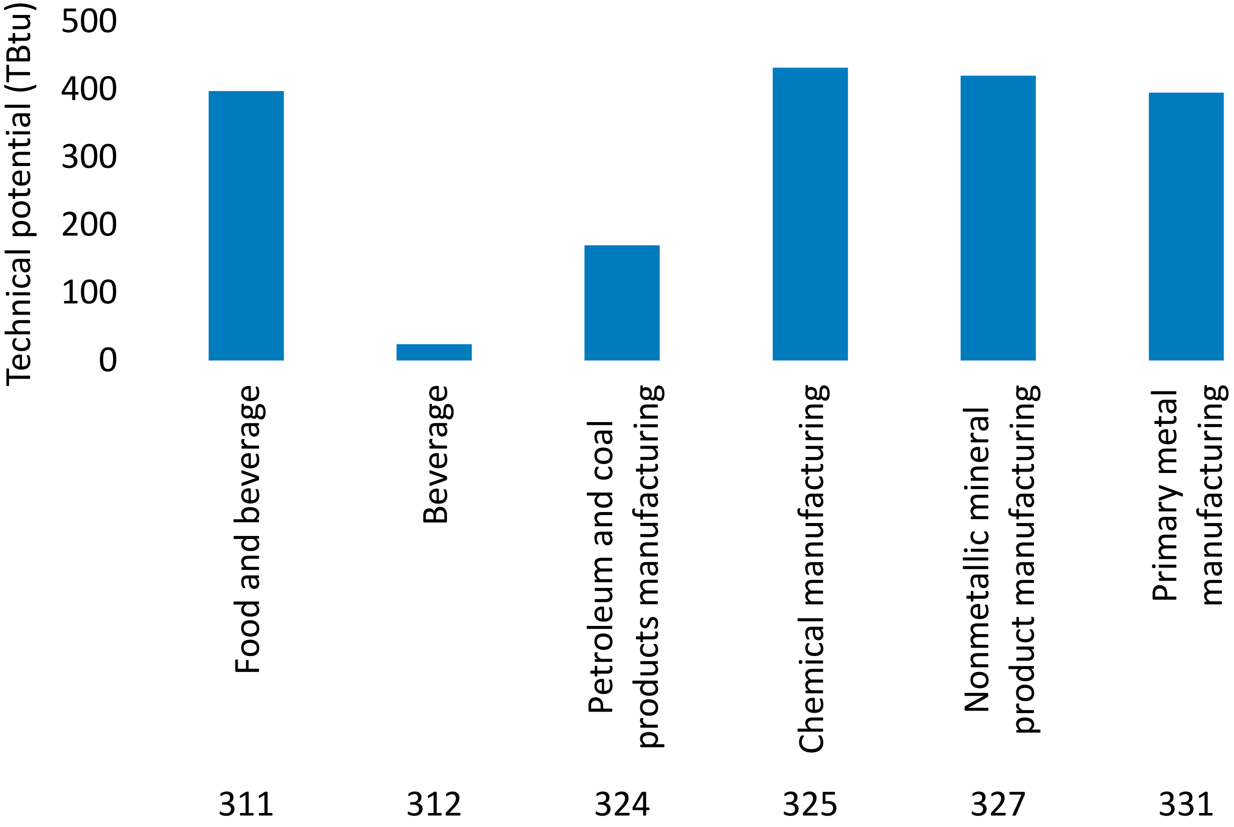
Thermal inertia per unit area of solar field 2.7 kJ/K-m2

Land Area

Solar field area 0.76148 acre
Non-solar field land area multiplier 1.2
Total land area 0.913776 acres

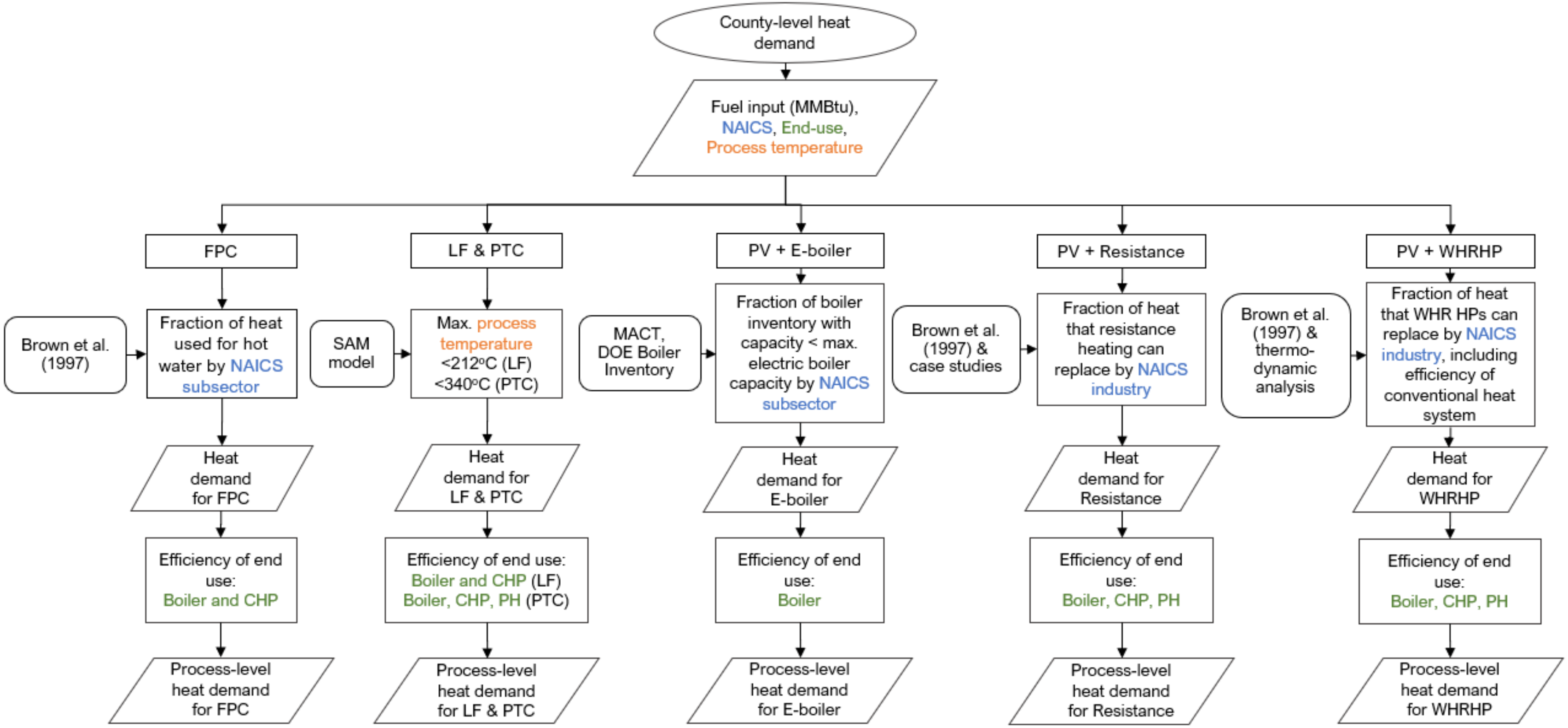
Unit Process Calculations

Technical potential of Resistance Heating and Melting



Total = 1,834 TBtu

Calculating Process Heat Demand



County-level heat demand

Fuel input (MMBtu), NAICS, End-use, Process temperature

FPC

Brown et al. (1997)

Fraction of heat used for hot water by NAICS subsector

Heat demand for FPC

Efficiency of end use: Boiler and CHP

Process-level heat demand for FPC

LF & PTC

SAM model

Max. process temperature <212°C (LF) <340°C (PTC)

Heat demand for LF & PTC

Efficiency of end use: Boiler and CHP (LF) Boiler, CHP, PH (PTC)

Process-level heat demand for LF & PTC

PV + E-boiler

MACT, DOE Boiler Inventory

Fraction of boiler inventory with capacity < max. electric boiler capacity by NAICS subsector

Heat demand for E-boiler

Efficiency of end use: Boiler

Process-level heat demand for E-boiler

PV + Resistance

Brown et al. (1997) & case studies

Fraction of heat that resistance heating can replace by NAICS industry

Heat demand for Resistance

Efficiency of end use: Boiler, CHP, PH

Process-level heat demand for Resistance

PV + WHRHP

Brown et al. (1997) & thermo-dynamic analysis

Fraction of heat that WHR HPs can replace by NAICS industry, including efficiency of conventional heat system

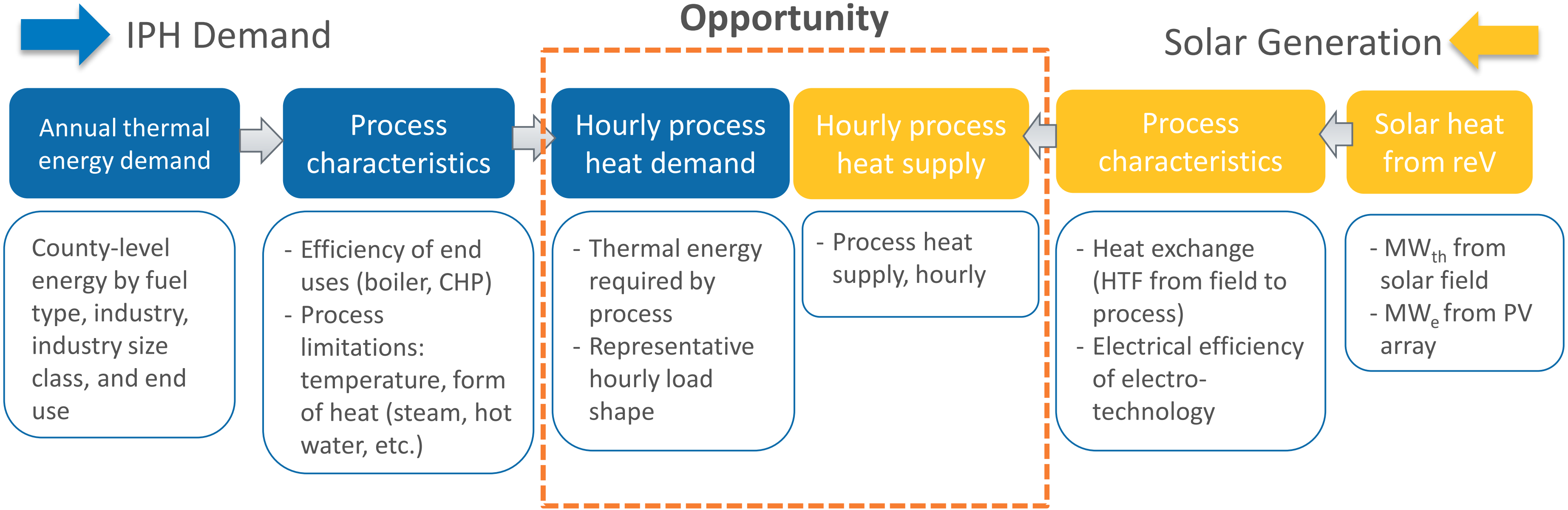
Heat demand for WHRHP

Efficiency of end use: Boiler, CHP, PH

Process-level heat demand for WHRHP

Results Backup

Opportunities: Calculation Framework



IPH Demand

Opportunity

Solar Generation

Annual thermal energy demand

County-level energy by fuel type, industry, industry size class, and end use

Process characteristics

- Efficiency of end uses (boiler, CHP)
- Process limitations: temperature, form of heat (steam, hot water, etc.)

Hourly process heat demand

- Thermal energy required by process
- Representative hourly load shape

Hourly process heat supply

- Process heat supply, hourly

Process characteristics

- Heat exchange (HTF from field to process)
- Electrical efficiency of electro-technology

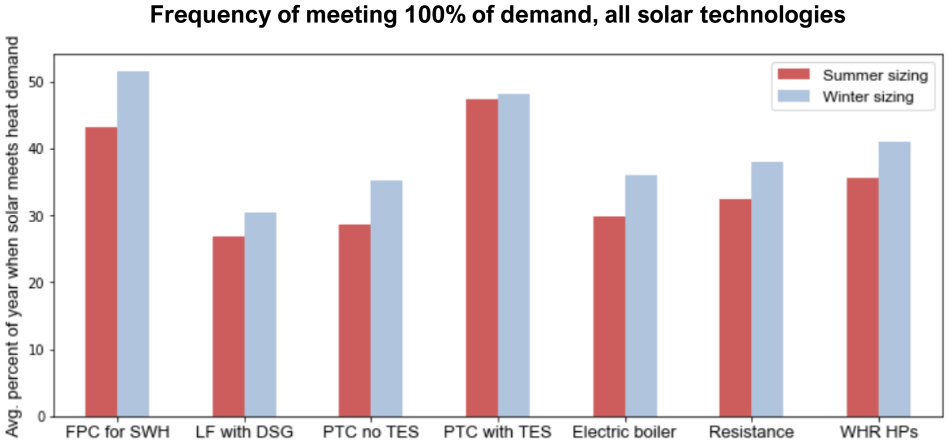
Solar heat from reV

- MW_{th} from solar field
- MW_e from PV array

Opportunity (% fossil fuel replaced) $= \sum \frac{energy\ provided\ to\ process\ by\ solar\ tech_{county,hour}}{energy\ required\ for\ process\ heat_{county,hour}}$

Comparison of summer and winter sizing

- Solar technologies meet demand more often with systems sized to meet peak load in winter



SWH = solar water heating; DSG = direct steam generation

CO_2 emissions savings

- CO_2 emissions were calculated based on fuel savings and CO_2 emissions factors by fuel type

CO_2 emissions savings (million metric tons)

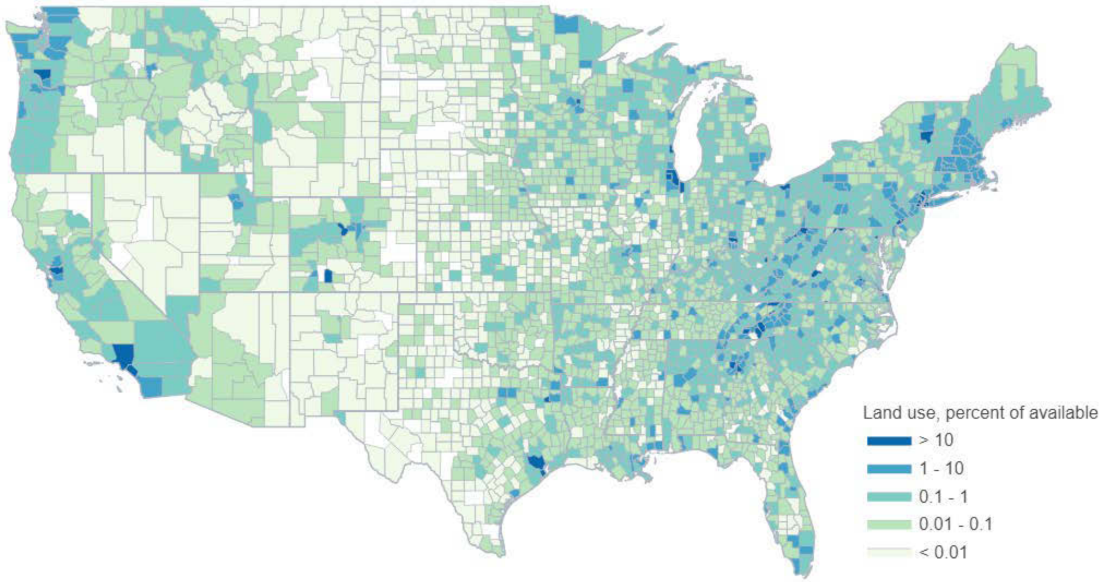
	FPC	LF DSG	PTC no TES	PTC w/ TES	E-boiler	Resistance	WHR HPs
Summer sizing	26.6	70.3	95.8	136.4	18.3	20.9	4.7
Winter sizing	32.2	75.4	106.2	137.4	18.1	18.7	5.3

- U.S. energy-related **CO_2 emissions from industry** in 2014
  - 1500 million metric tons

EIA Monthly Energy Review, Table 11.4

Land Use Requirements

Land use as percentage of available land

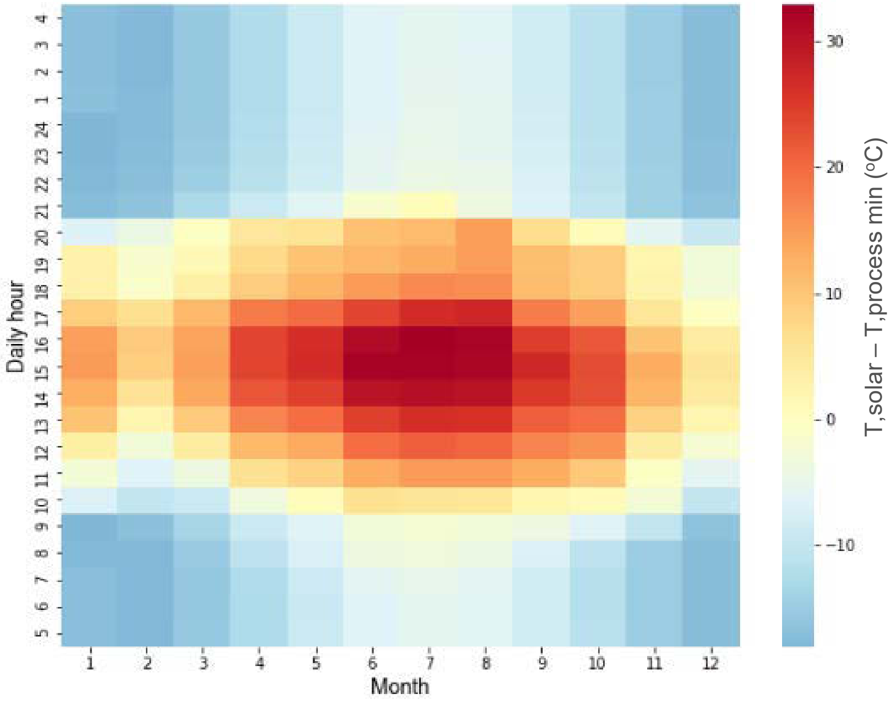


PV + Electric boiler

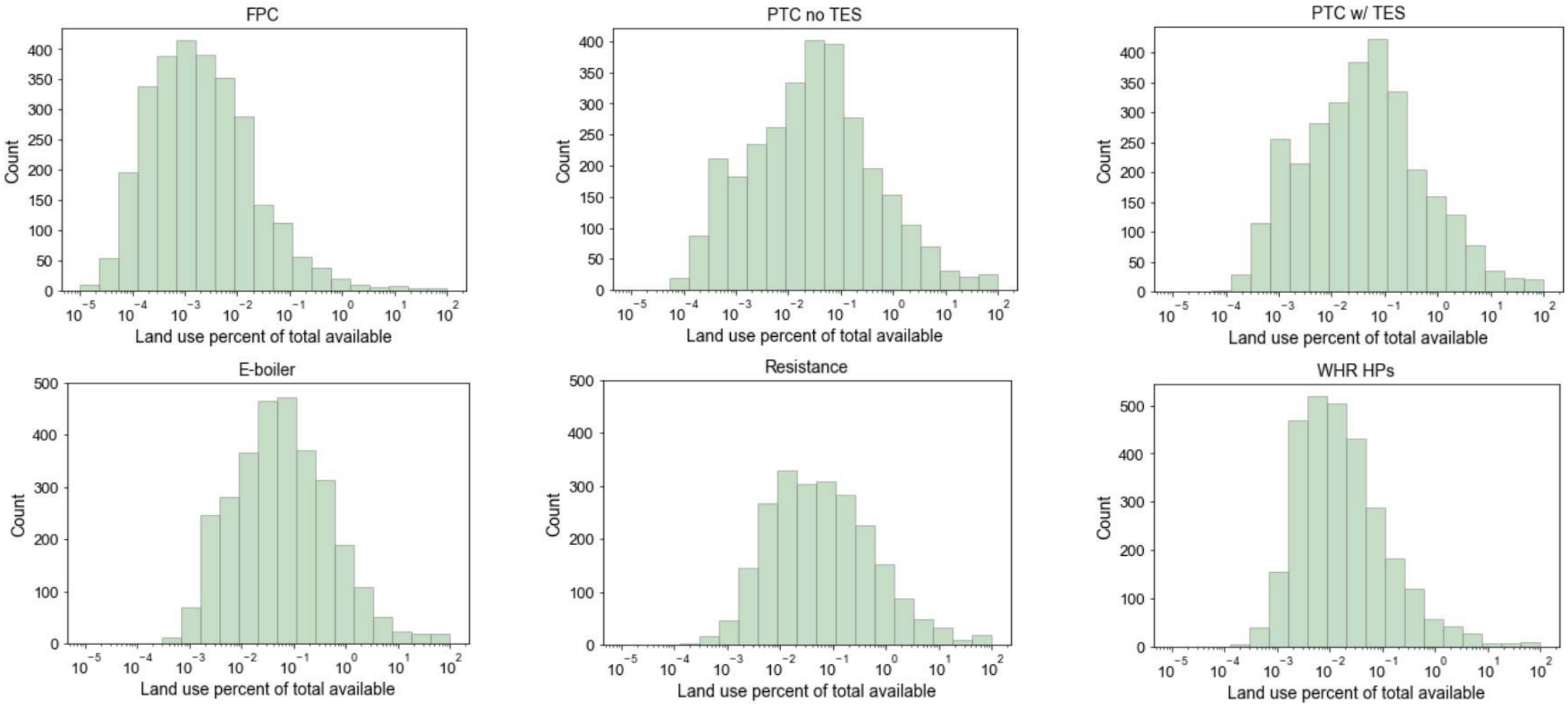
Hourly process temperatures and solar supplied temperatures

- Colors indicate the temperature difference between the minimum required process temperature in Bee County, TX and the solar supplied heat for an FPC hot water heating system

- FPC achieves the required process temperature during daytime hours and into the night during summer, due to warmer ambient temperatures and the included storage



Land use as a percentage of available land, histogram of counties

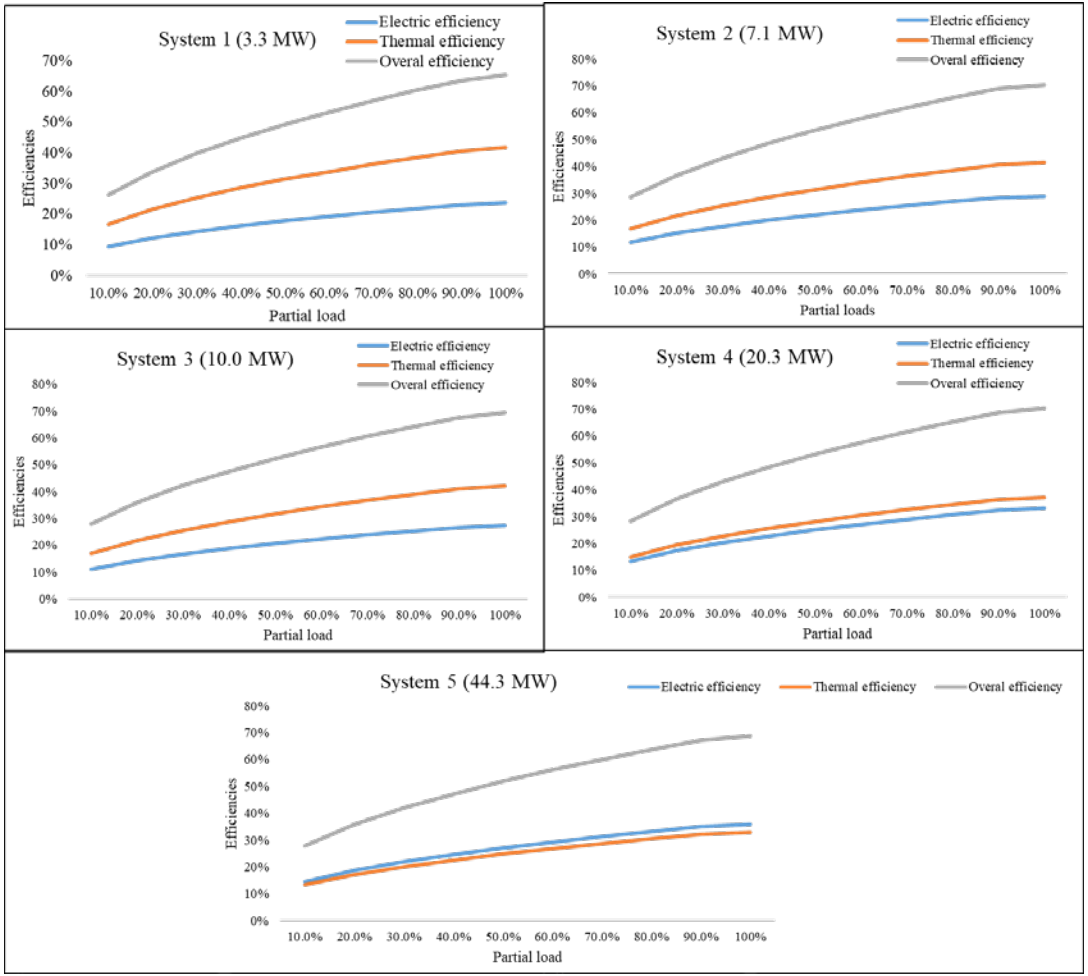


Additional Electricity needed for PV+electrotechnologies when not meeting demand

	Resistance	WHR HPs
Summer sizing	965 (944, 975)	225 (221, 228)
Winter sizing	642 (613, 659)	218 (215, 220)

CHP Calculations

Efficiency variations with partial thermal loads of combustion/gas turbine CHPs



Efficiency variations with partial thermal load of steam turbine CHPs