Solar Thermal

Renewable Thermal Technology

RENEWABLE
THERMAL
COLLABORATIVE

Technology Overview

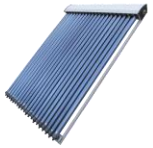
Description of technology

- Solar thermal technologies captures radiant solar energy and directly converts it to heat, which can be stored or used in industrial applications
- There are 2 main types of solar thermal technology
  - Non-concentrating
  - Concentrating
- Concentrated Solar Power (CSP) generates electricity using collected solar heat. PV-electric heating converts sunlight to electricity, which is then used to power electric heating technologies. These two adjacent technologies are not discussed in detail in this fact base but should be noted as potential competitors for solar resources.

Types of equipment

- Non-concentrating
  - Flat plate
  - Evacuated tube
  - Integral collector storage
  - Thermosiphon collector
- Concentrating
  - Parabolic trough
  - Parabolic dish
  - Power tower
  - Linear Fresnel


Flat plate collector


Evacuated tube collector


Parabolic trough


Linear fresnel

1. Onosi Solar flat plate collector; 2. Bimble Solar evacuated tube; 3. Telectronica parabolic trough; 4. US DOE linear concentrating solar
Note: Example equipment not exhaustive

Technical characteristics

- **Temperature ranges:** Practically up to 500 ºC
  - Non-concentrating: Up to 100 ºC
  - Concentrating: Theoretically up to 1,200 ºC
  - Molten salt thermal storage: Theoretically up to 560 ºC
- **Heat flux:** High heat flux
  - Dependent on scale of solar arrays and heat exchanger configuration
- **Heated materials:** Most materials are applicable
- **Emissions:** Zero emissions
- **Technical maturity:** Medium to high maturity
  - Non-concentrating low temperature solar thermal widely deployed for residential & commercial building water heating
  - Concentrating higher temperature industrial heating at pilot and demonstrating phases in US

Solar thermal is applicable to most low and medium temperature industrial heating processes

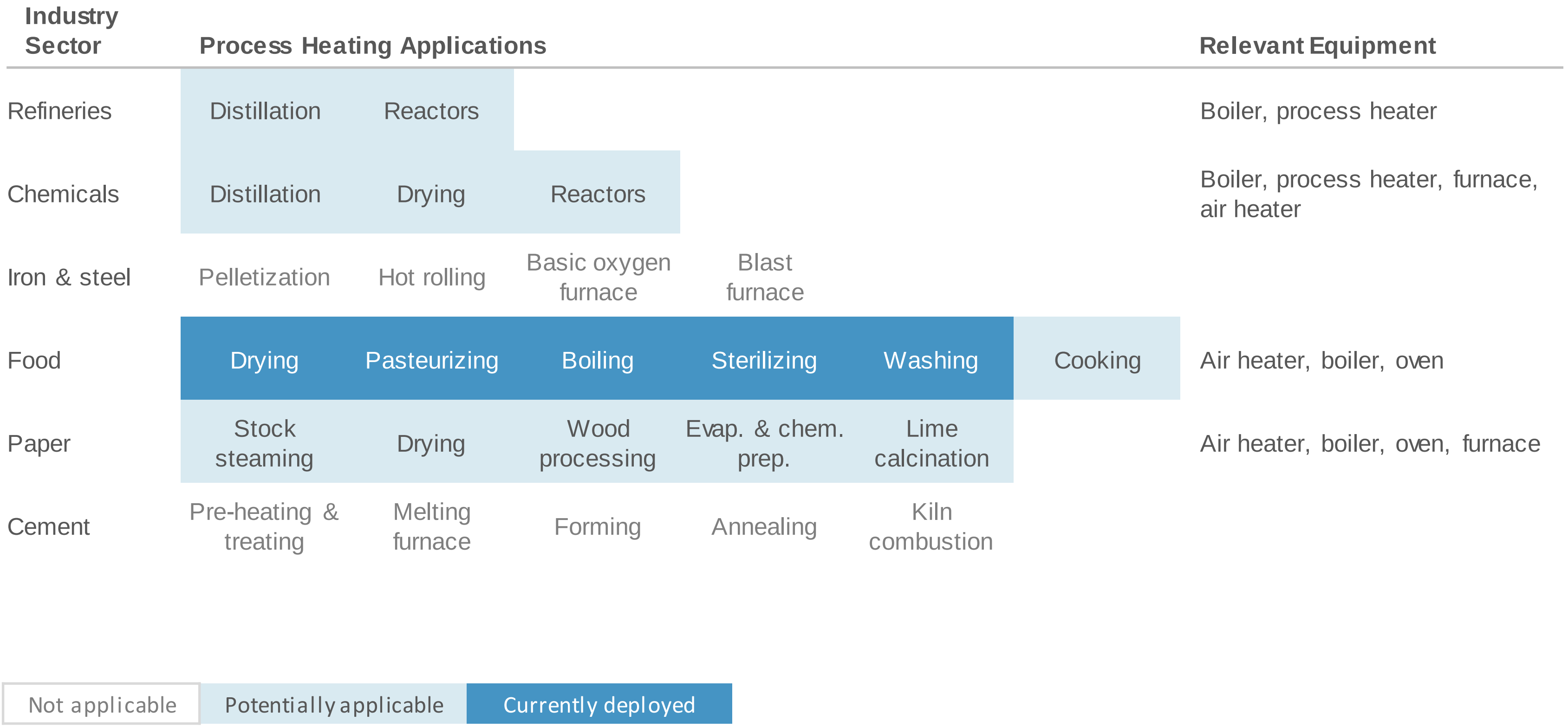
Key properties of solar thermal heating include:

1,200 °C max. temp.

High heat flux

Heats most materials

These properties align with requirements for several process heating applications.

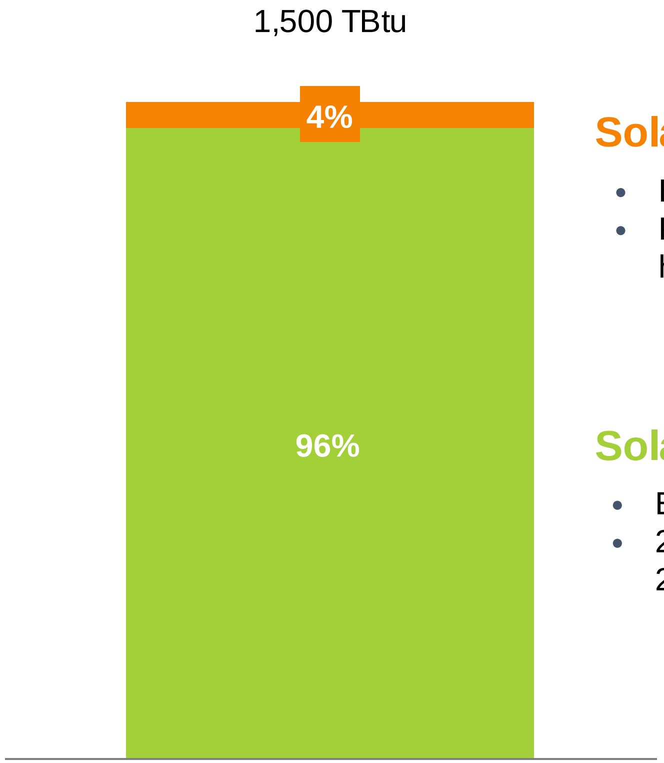


Industry Sector	Process Heating Applications						Relevant Equipment
Refineries	Distillation	Reactors					Boiler, process heater
Chemicals	Distillation	Drying	Reactors				Boiler, process heater, furnace, air heater
Iron & steel	Pelletization	Hot rolling	Basic oxygen furnace	Blast furnace			
Food	Drying	Pasteurizing	Boiling	Sterilizing	Washing	Cooking	Air heater, boiler, oven
Paper	Stock steaming	Drying	Wood processing	Evap. & chem. prep.	Lime calcination		Air heater, boiler, oven, furnace
Cement	Pre-heating & treating	Melting furnace	Forming	Annealing	Kiln combustion		

Not applicable | Potentially applicable | Currently deployed

While total US solar energy use has grown rapidly in the last two decades, solar thermal currently constitutes a small proportion

Total solar energy in US (2021)



Solar thermal

- Efficiency: Can operate up to 70%
- Primarily used for domestic water heating today

Solar electricity

- Efficiency: Approaching 20%
- 2.8% of total electricity generation in 2020, and growing rapidly

Studies find that solar thermal could provide up to **25% of total US industrial heating demand**, with key constraining factors to deployment being:

- Resource potential (e.g., spatial, temporal)
- Integration of solar heat with existing industrial loads

Source: David Gardiner and Associates, US EIA, NREL

Technical viability of industrial solar thermal technologies depends on the alignment of three key factors

Spatial

Locations for process heat demand must match the supply of solar resources nearby

Temporal

Seasonal and hourly demand for process heat must align with the timing of solar thermal supply

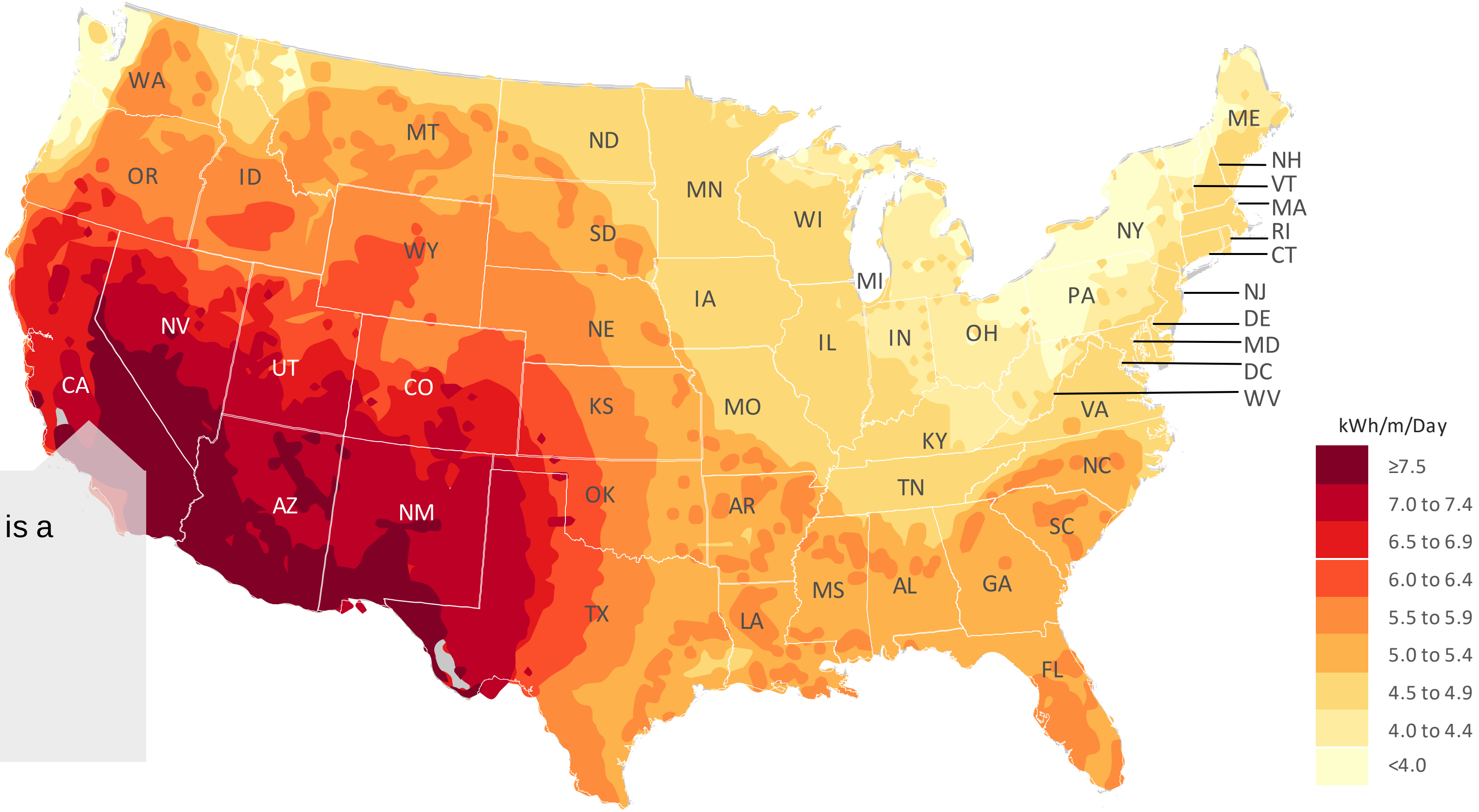
Temperature

Solar thermal technology should deliver requisite process heat temperatures and other requirements

Spatial | Within the US, the Southwest has the highest level of annual solar irradiation

Other important geographical factors to determine the viability of industrial solar thermal include:

- Matching thermal supply with demand at appropriate temperatures
- Land availability



Example: California's central valley is a promising area with:

- Rich solar resources
- Potentially available land
- Thermal demand from food and agricultural sectors

Source: NREL

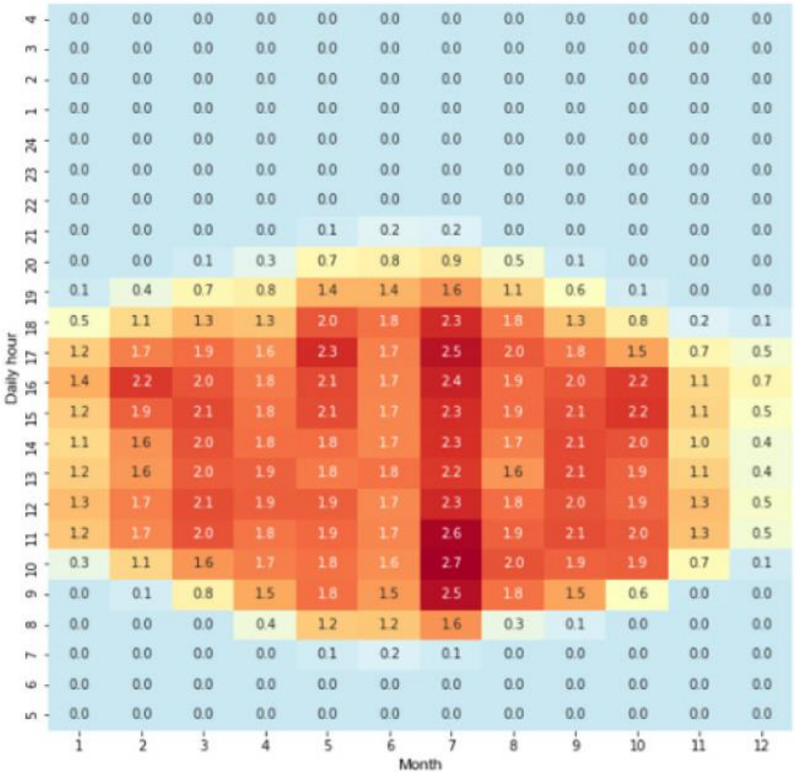
Temporal | Intermittency of heat supply is a major limitation of widespread solar thermal technology deployment in industry

To decrease the impact of solar thermal intermittency, the process operator can implement several strategies

- Design process to be compatible with irregular and low equipment utilization
- Deployment of back-up dispatchable thermal energy sources
- Deployment of thermal energy storage

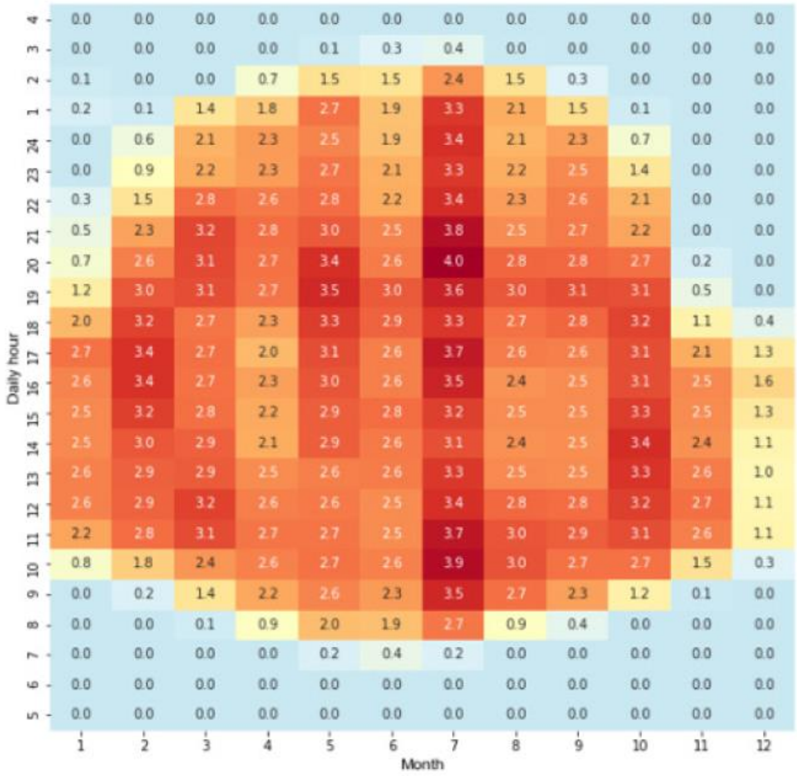
Temporal | Thermal energy storage can provide substantially more process heating potential beyond the limited hours of high solar irradiation

Example solar fraction[1] of a parabolic trough collector (PTC) system in Polk County, IA



Daily hour	1	2	3	4	5	6	7	8	9	10	11	12
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.1	0.3	0.7	0.8	0.9	0.5	0.1	0.0	0.0	0.0
19	0.1	0.4	0.7	0.8	1.4	1.4	1.6	1.1	0.6	0.1	0.0	0.0
18	0.5	1.1	1.3	1.3	2.0	1.8	2.3	1.8	1.3	0.8	0.2	0.1
17	1.2	1.7	1.9	1.6	2.3	1.7	2.5	2.0	1.8	1.5	0.7	0.5
16	1.4	2.2	2.0	1.8	2.1	1.7	2.4	1.9	2.0	2.2	1.1	0.7
15	1.2	1.9	2.1	1.8	2.1	1.7	2.3	1.9	2.1	2.2	1.1	0.5
14	1.1	1.6	2.0	1.8	1.8	1.7	2.3	1.7	2.1	2.0	1.0	0.4
13	1.2	1.6	2.0	1.9	1.8	1.8	2.2	1.6	2.1	1.9	1.1	0.4
12	1.3	1.7	2.1	1.9	1.9	1.7	2.3	1.8	2.0	1.9	1.3	0.5
11	1.2	1.7	2.0	1.8	1.9	1.7	2.6	1.9	2.1	2.0	1.3	0.5
10	0.3	1.1	1.6	1.7	1.8	1.6	2.7	2.0	1.9	1.9	0.7	0.1
9	0.0	0.1	0.8	1.5	1.8	1.5	2.5	1.8	1.5	0.6	0.0	0.0
8	0.0	0.0	0.0	0.4	1.2	1.2	1.6	0.3	0.1	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

PTC without thermal storage



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4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.1	0.3	0.4	0.0	0.0	0.0	0.0	0.0
2	0.1	0.0	0.0	0.7	1.5	1.5	2.4	1.5	0.3	0.0	0.0	0.0
1	0.2	0.1	1.4	1.8	2.7	1.9	3.3	2.1	1.5	0.1	0.0	0.0
24	0.0	0.6	2.1	2.3	2.5	1.9	3.4	2.1	2.3	0.7	0.0	0.0
23	0.0	0.9	2.2	2.3	2.7	2.1	3.3	2.2	2.5	1.4	0.0	0.0
22	0.3	1.5	2.8	2.6	2.8	2.2	3.4	2.3	2.6	2.1	0.0	0.0
21	0.5	2.3	3.2	2.8	3.0	2.5	3.8	2.5	2.7	2.2	0.0	0.0
20	0.7	2.6	3.1	2.7	3.4	2.6	4.0	2.8	2.8	2.7	0.2	0.0
19	1.2	3.0	3.1	2.7	3.5	3.0	3.6	3.0	3.1	3.1	0.5	0.0
18	2.0	3.2	2.7	2.3	3.3	2.9	3.3	2.7	2.8	3.2	1.1	0.4
17	2.7	3.4	2.7	2.0	3.1	2.6	3.7	2.6	2.6	3.1	2.1	1.3
16	2.6	3.4	2.7	2.3	3.0	2.6	3.5	2.4	2.5	3.1	2.5	1.6
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11	2.2	2.8	3.1	2.7	2.7	2.5	3.7	3.0	2.9	3.1	2.6	1.1
10	0.8	1.8	2.4	2.6	2.7	2.6	3.9	3.0	2.7	2.7	1.5	0.3
9	0.0	0.2	1.4	2.2	2.6	2.3	3.5	2.7	2.3	1.2	0.1	0.0
8	0.0	0.0	0.1	0.9	2.0	1.9	2.7	0.9	0.4	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.2	0.4	0.2	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

PTC with 6 hours thermal storage (28% greater)

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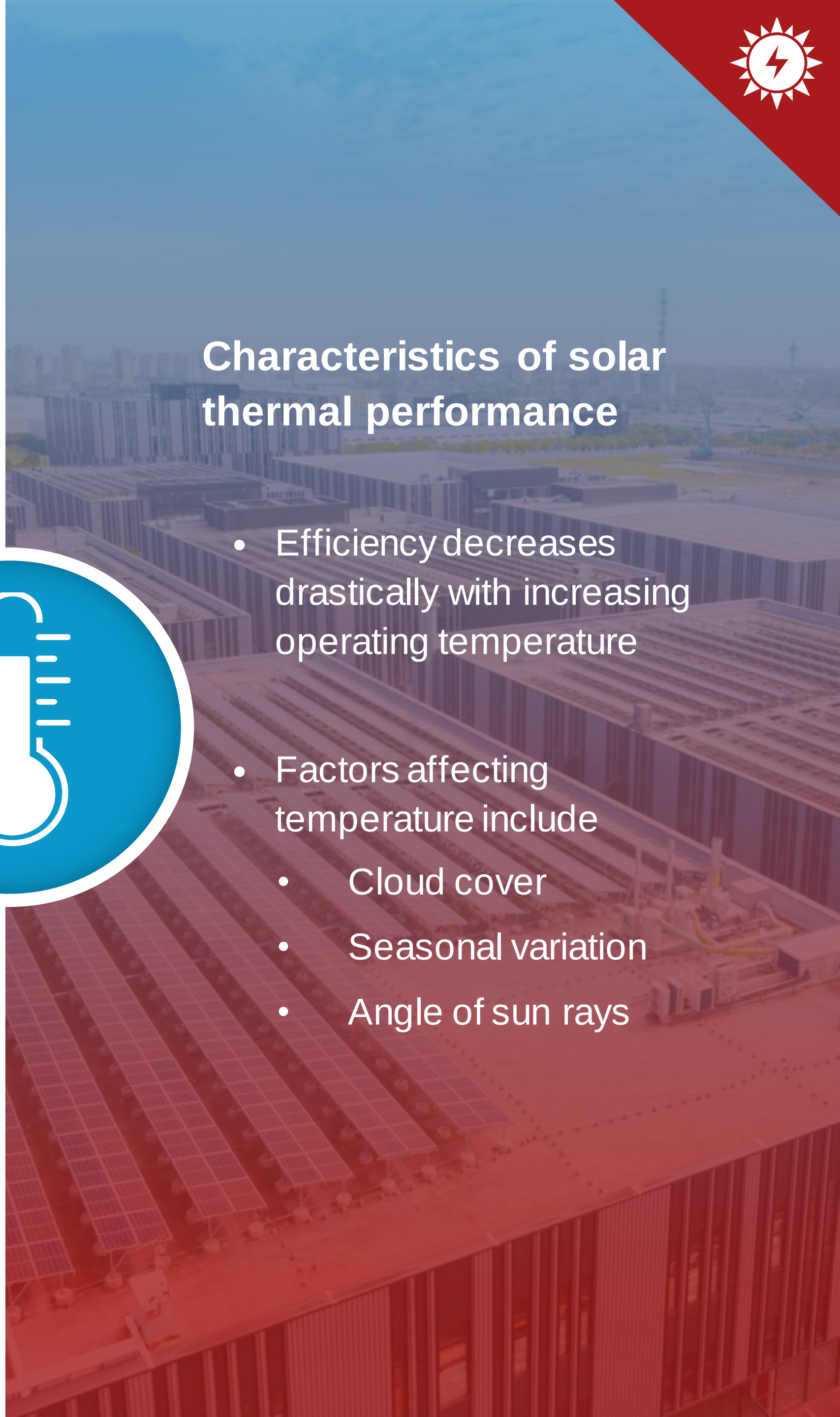
1. Potential contribution of solar energy to the total load

Source: NREL

Temperature | Non-concentrating solar thermal can provide up to 100°C, while concentrating solar thermal can deliver up to 1,200 °C

Solar thermal technology	Operating temperatures
Non-concentrating	<100 °C
Parabolic trough	260-400 °C
Linear Fresnel	260-400 °C
Power tower	600-1,000 °C
Parabolic dish	500-1,200 °C
Molten salt storage	<560 °C

Source: ARENA

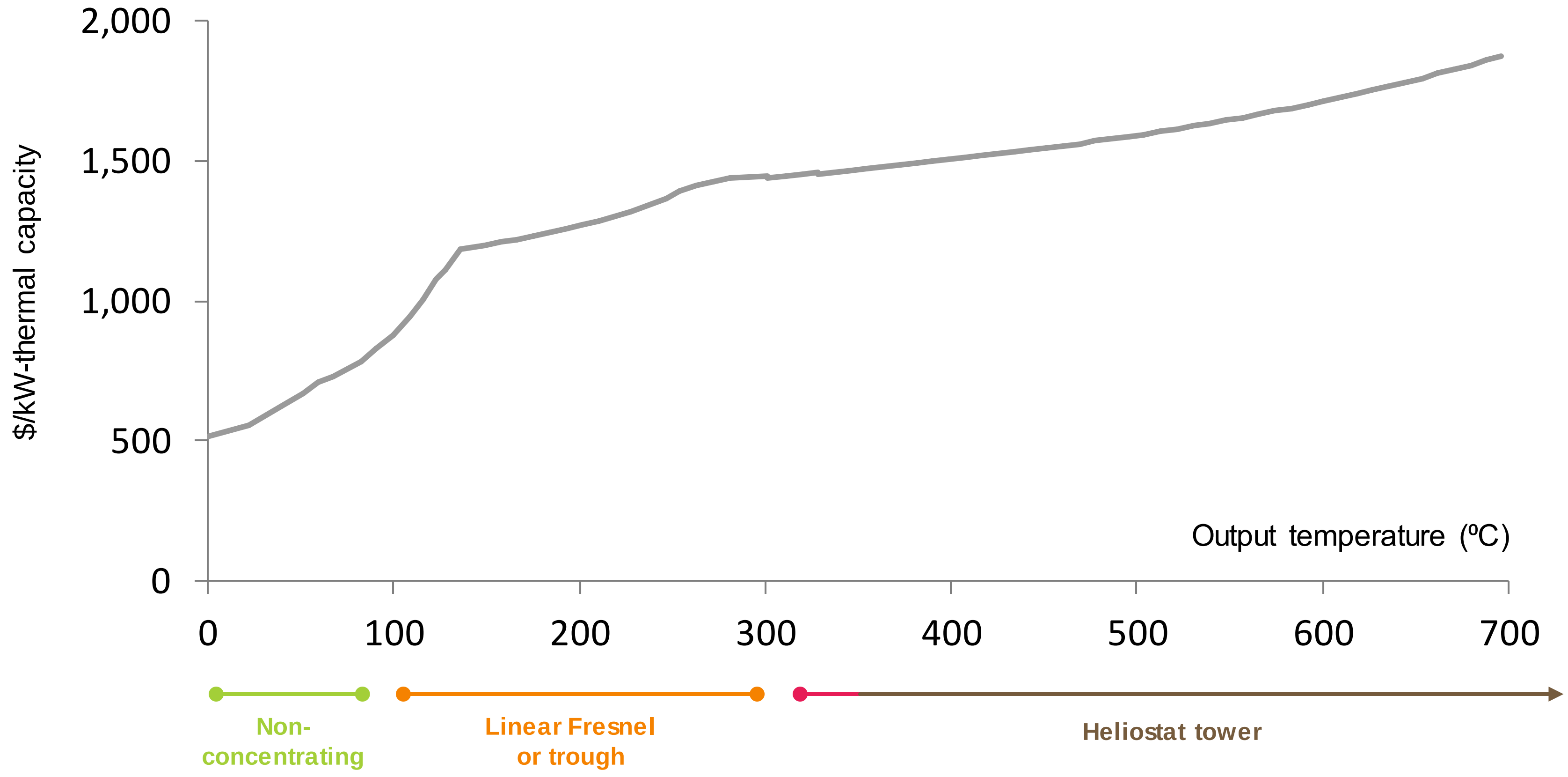


Characteristics of solar thermal performance

- Efficiency decreases drastically with increasing operating temperature
- Factors affecting temperature include
  - Cloud cover
  - Seasonal variation
  - Angle of sun rays

Two key determinates of solar thermal capital costs are the technology type and the output temperature

Lowest capital costs for solar thermal equipment in each temperature range

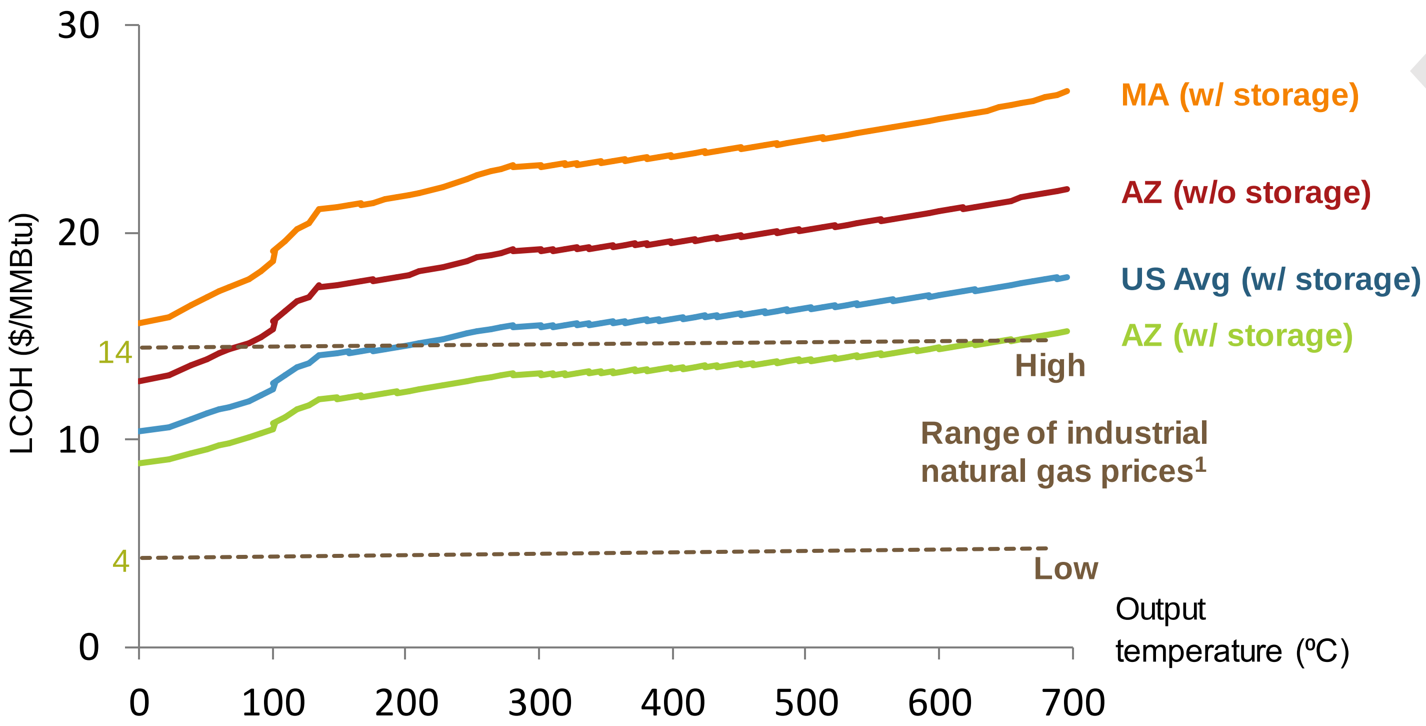


Solar thermal heating cost **increases with output temperatures**

Source: ARENA

Industrial solar heating can be cost effective depending on configuration and location

US Levelized Cost of Heat for Solar Thermal



[1] EIA May 2022 end-user prices

Notes: Does not include cost for land use. Uses solar thermal power plant estimates (central receiver tower with heliostats) with power generation equipment removed for LCOH calculation.

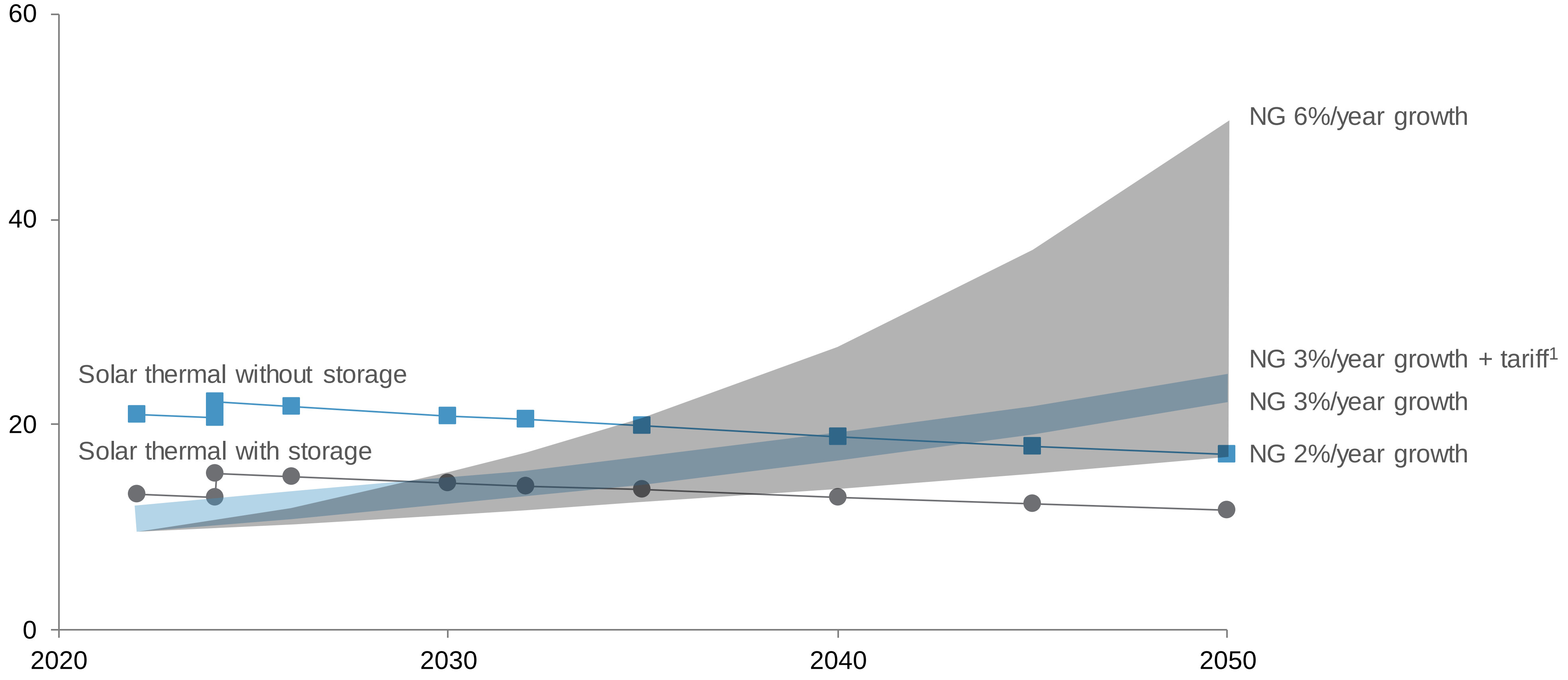
Source: NREL; Lazard; IRENA; DOE, AIP Conference Proceedings; BCG analysis

Economic viability of solar LCOH depends on several factors

- **Process specifications**
  - Output temperature
  - Solar heating technology type
  - Deployment of thermal storage
- **Location**
  - Solar irradiance
  - Land availability
  - Proximity of heat production and use
  - Ambient temperature
- **Financial**
  - Discount rate
  - Equipment lifetime

Pairing solar thermal with storage can expand geographic and sector applicability, and reach cost parity with natural gas in the medium term

Average US LCOH ($/MMBtu)



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[1] Based on $51/tonne CO2 social cost of carbon

Note: Subsidized are shown in plots, subsidized and unsubsidized LCOHs are within 15%

Potential consumers of industrial heat may deprioritize onsite land use for solar thermal due to competing applications

Electricity generation

Electricity generation via PV[1] or CSP[2] may provide better financial return for an equivalent level of land use

Agricultural uses

Solar thermal is most readily applicable to food and agricultural processes, but land use competes with growing crops and raising livestock

Expansion of processing facilities

Plans for expanding industrial facilities may out-compete land use for solar thermal heat collection

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1. Photovoltaic; 2. Concentrated solar power

Solar thermal industrial heating has several advantages, but faces several major hurdles to adoption

Advantages

- Zero fuel costs and low operating costs
- Able to offset a portion of facility thermal demand
- Potential to pair with thermal energy storage
- Zero emissions and no combustion

Barriers

- Geographically constrained to high insolation areas
- Large footprint
- Limited to low and medium temperature applications
- Seasonal and diurnal intermittency leading to risk of process disruption

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