Renewable Thermal Energy Systems Designed for Industrial Process Solutions in Multiple Industries

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Content

1. Background

- Global industrial heating applications, the majority being process heat related, have been estimated to be approximately 20% of the total global energy consumed (IRENA, 2019).
- Recent work from the National Renewable Energy Laboratory (NREL) indicate that nearly 2/3 of the industrial thermal demand in 2014 in the United States is less than 300°C, which is ideally suited to solar and renewable heat systems (McMillan et al., 2021).
- Renewable thermal energy systems (RTES), either in stand-alone or hybrid configurations hold good potential to provide low to medium temperature heat less than 300°C (Akar et al., 2021), with the need for costs to decrease to increase deployment. Two areas examined in this paper were food/beverage processing and district heating.

(IRENA 2019) - https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Power-to-heat_2019.pdf?la=en&hash=524C1BFD59EC03FD44508F8D7CFB84CEC317A299
(McMillan et al., 2021) - https://www.nrel.gov/docs/fy21osti/77760.pdf
(Akar et al. 2021) - https://www.nrel.gov/docs/fy21osti/79675.pdf

2. Introduction

- This paper highlights the application of the hybrid RTES framework and newly developed code modules for specific case studies.

- The models and results explore the techno-economic analysis (TEA) s and potential of stand-alone and hybrid RTES applied to a potential food processing and district heating and food processing applications. Two main case studies are explored in detail.

- This paper builds work upon work and the opportunities identified for SIPH in the U.S. (McMillan et al., 2021), and looks to focus it on specific industries of interest and high economic potential.

MODELED RTES CASES

High Temperature Heat Pump (HTHP) System for District Heating

Linear Fresnel collectors (LFCs) coupled with phase change material (PCM) thermal energy storage (TES) for Food & Beverage Industry

3. High Temperature Heat Pump (HTHP) System for District Heating

Heat Pump System for District Heating

- In heat pump-driven district heating systems, the most common sources of heat are sewage water, ambient water, and industrial waste heat which can deliver hot water between 60°C and 90°C.

- Most operating heat pump-driven district heating systems in Europe use either R134a or ammonia as refrigerants.

- Heat Pumps would perform district heating functions using common heat sources and in combination with solar technologies.

Source: Arpagaus 2020. "Industrial Heat Pumps in Switzerland." SFOE

Capital Costs & Operating Temperatures for Heat Pumps

Capital costs and operating temperature ranges for heat pumps.

Case	Source Heat Temperature	Capital Cost	Output Temperatures
Ambient Water – Low Cost	5°C	$150/kW	50°C, 60°C, 70°C, 80°C, 90°C
Ambient Water – High Cost		$300/kW	
Sewage – Low Cost	20°C	$150/kW	
Sewage – High Cost		$300/kW	
Solar Flat Plate – Low Cost	35°C	$700/kW	
Solar Flat Plate – High Cost		$850/kW	

- **Inputs**
  - Three different source heat temperatures
  - High and low capital cost scenarios for each source
  - Five different output temperatures

Coefficient of Performance (COP) for Heat Pumps

Resulting COP from the heat pump model based on available source temperature

	COP				
Output Temperature	50°C	60°C	70°C	80°C	90°C
Ambient Water / 5°C	**4.50**	**3.74**	**3.19**	**2.78**	**2.45**
Sewage / 20°C	**6.92**	**5.30**	**4.31**	**3.65**	**3.17**
Solar Concentrator / 35°C	**14.02**	**8.62**	**6.30**	**5.00**	**4.16**

- As expected, system COP is inversely related to the magnitude of temperature lift
  - Lowest temperature lift (15°C, bottom left) has the highest COP
  - Highest temperature lift (85°C, top right) has the lowest COP

HTHP System for District Heating

Resulting LCOH for temperature and cases

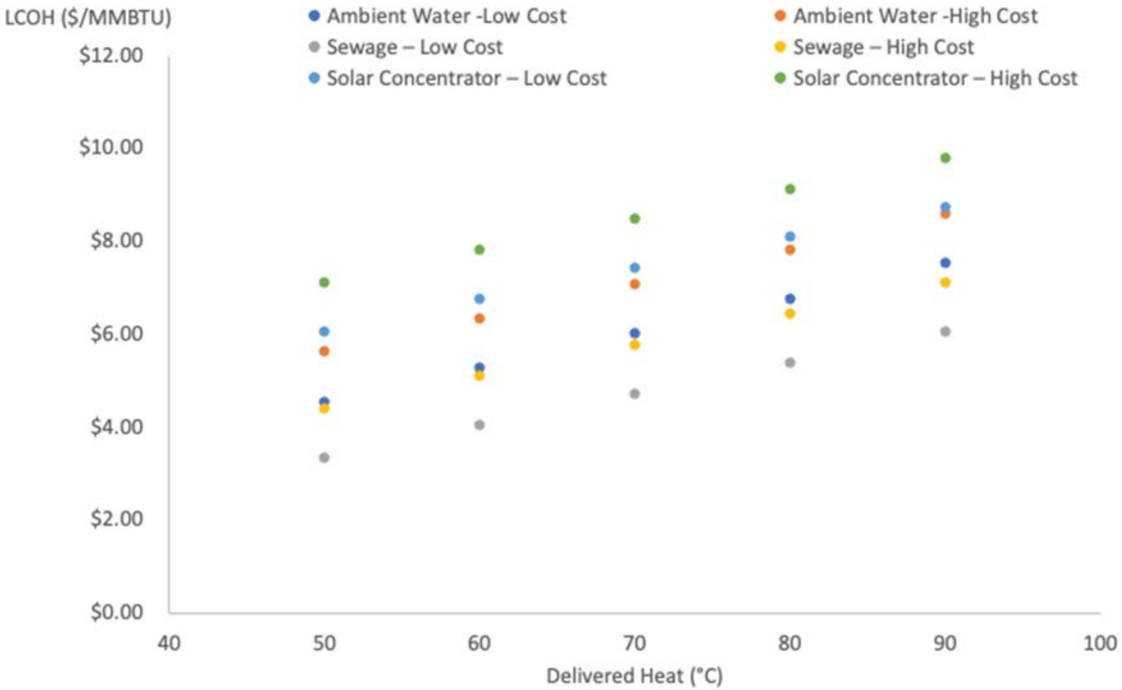
	LCOH ($/MMBTU)				
	50°C	60°C	70°C	80°C	90°
Ambient Water -Low Cost	**$4.56**	**$5.29**	**$6.03**	**$6.76**	**$7.53**
Ambient Water -High Cost	**$5.63**	**$6.35**	**$7.08**	**$7.81**	**$8.58**
Sewage – Low Cost	**$3.35**	**$4.05**	**$4.73**	**$5.40**	**$6.06**
Sewage – High Cost	**$4.40**	**$5.10**	**$5.79**	**$6.45**	**$7.11**
Solar Concentrator – Low Cost	**$6.05**	**$6.76**	**$7.44**	**$8.09**	**$8.73**
Solar Concentrator – High Cost	**$7.10**	**$7.81**	**$8.49**	**$9.14**	**$9.78**

- The results show that the solar concentrator’s additional capital costs are too high to be fully offset by the increase in heat pump performance
  - Using sewage as the heat source provides the lowest LCOH for a given output temperature

HTHP System for District Heating

- In the case of installing a solar collector to provide input heat, additional capital costs increased the LCOH of this system's heat above that of the ambient water heat pump system's, meaning that the solar collector/heat pump system is likely not the most economic option.

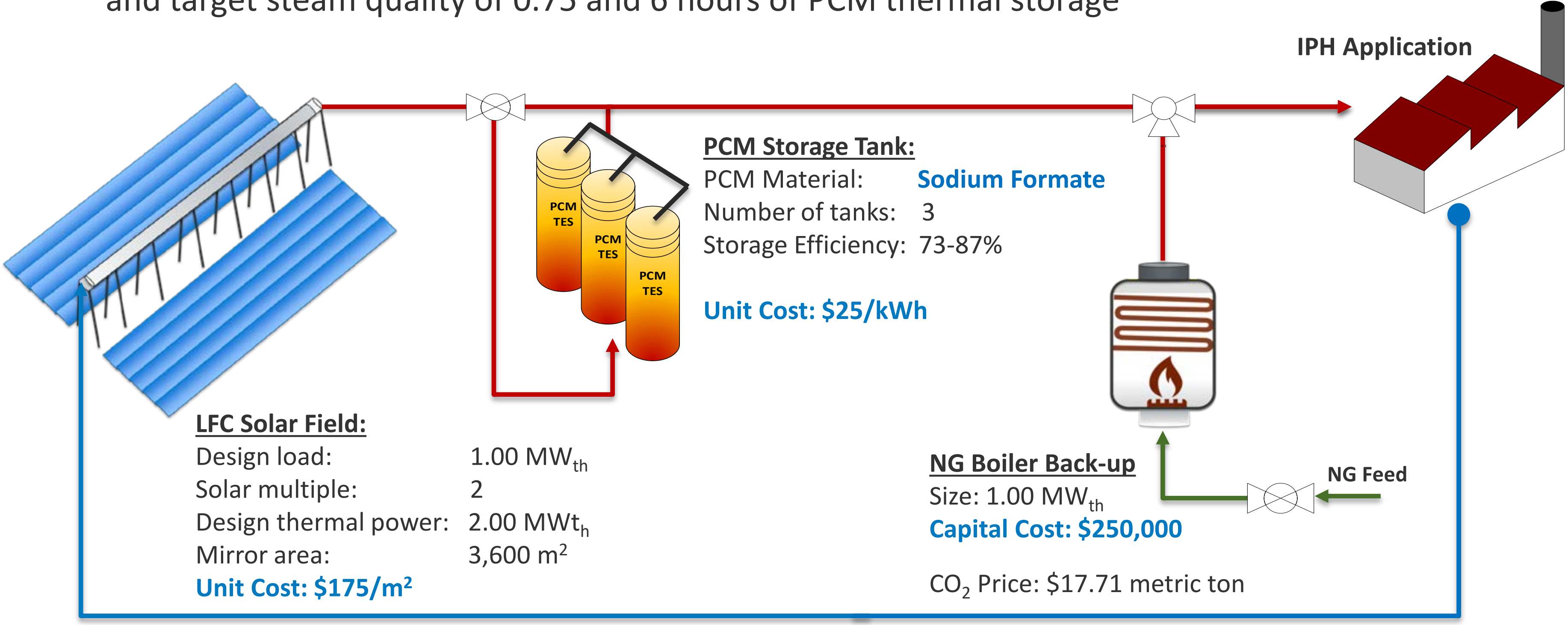
Levelized cost of Heat (LCOH) for different types of heat pumps and the delivered heat of the scenarios.



4. Linear Fresnel collectors (LFCs) coupled with phase change material (PCM) thermal energy storage (TES) for Food & Beverage Industry

LFC PCM-TES System Design

- The LFC-DSG system is designed for a 1 MW_{th} capacity with a solar multiple of 2 (~3,600 m^2) and target steam quality of 0.75 and 6 hours of PCM thermal storage



PCM Storage Tank:
PCM Material: **Sodium Formate**
Number of tanks: 3
Storage Efficiency: 73-87%

Unit Cost: $25/kWh

LFC Solar Field:
Design load: 1.00 MW_{th}
Solar multiple: 2
Design thermal power: 2.00 MWt_h
Mirror area: 3,600 m^2
Unit Cost: $175/m²

NG Boiler Back-up
Size: 1.00 MW_{th}
Capital Cost: $250,000

CO_2 Price: $17.71 metric ton

Heat Load & Generation Profile for California

Location / Solar DNI
Lancaster, California, 7.93 kWh/m²/day

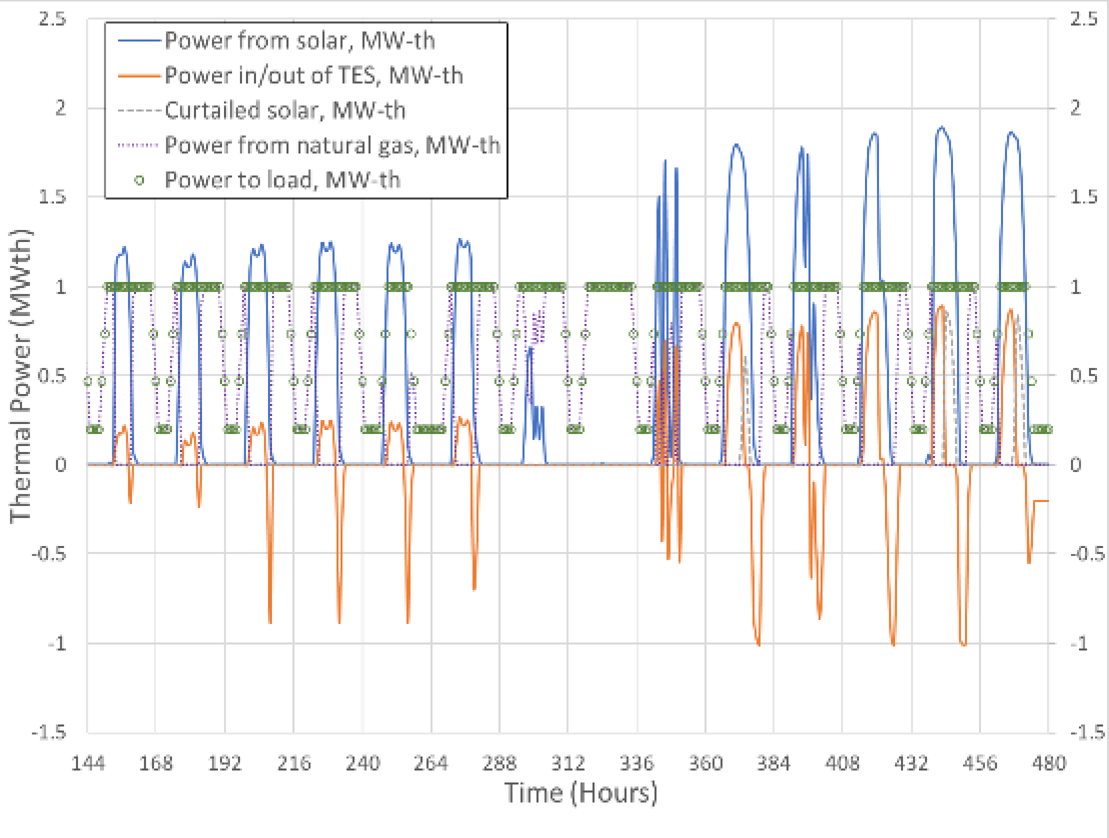
Heat Load
6am-8am: Ramping up to 0.47 – 0.75 MW_{th}
8am-10pm: 1 MW_{th} constant
10pm-12pm: Ramping down to 0.75 - 0.47 MW_{th}
12pm-6am: 0.2 MW_{th} constant

Natural Gas Price:
- $0.025 kWh/ $7.37 MMBTU

PCM-TES Storage:
- 6 Hours

LFC Cost:
- 175 $/m²

PCM Thermal Storage System Cost:
- 25 $/$kWh_{th}$



Representative two-week timeline (one week from winter and one week summer) in California

Parametric Analysis

- Alternative cases for parametric analysis are adjusted for 6 and 12 hours of storage with a solar multiple between 1.5 (~2,700 m^2), 2.0 (3,600 m^2) and 2.5 (~4,500 m^2).

State	Solar Field (m^2)	Storage Duration (hours)	Solar Share in Total Load (%)	Curtailed Solar Energy (%)	Storage Efficiency (%)	LCOH (Hybrid) $\$/kWh_{th}$	LCOH (Hybrid) $/MMBTU	LCOH with CO2 adder $/kWhth	LCOH without CO2 adder $/MMBTU
PA	2,890	6	26.01%	2.02%	63.41%	0.047	13.89	0.045	13.07
PA	3,973	6	34.33%	4.57%	78.79%	0.049	14.26	0.046	13.54
PA	4,966	12	41.32%	0.32%	60.57%	0.051	14.95	0.052	15.17
CA	2,700	6	40.33%	1.78%	89.21%	0.041	11.92	0.038	11.26
CA	3,600	6	50.98%	6.46%	84.70%	0.041	11.98	0.039	11.44
CA	4,501	12	63.32%	0.61%	72.76%	0.042	12.23	0.043	12.51
AZ	2,667	6	39.90%	1.68%	64.19%	0.032	9.43	0.030	8.68
AZ	3,556	6	51.69%	6.85%	87.19%	0.034	9.85	0.032	9.41
AZ	4,455	12	64.42%	3.21%	79.32%	0.035	10.40	0.037	10.87

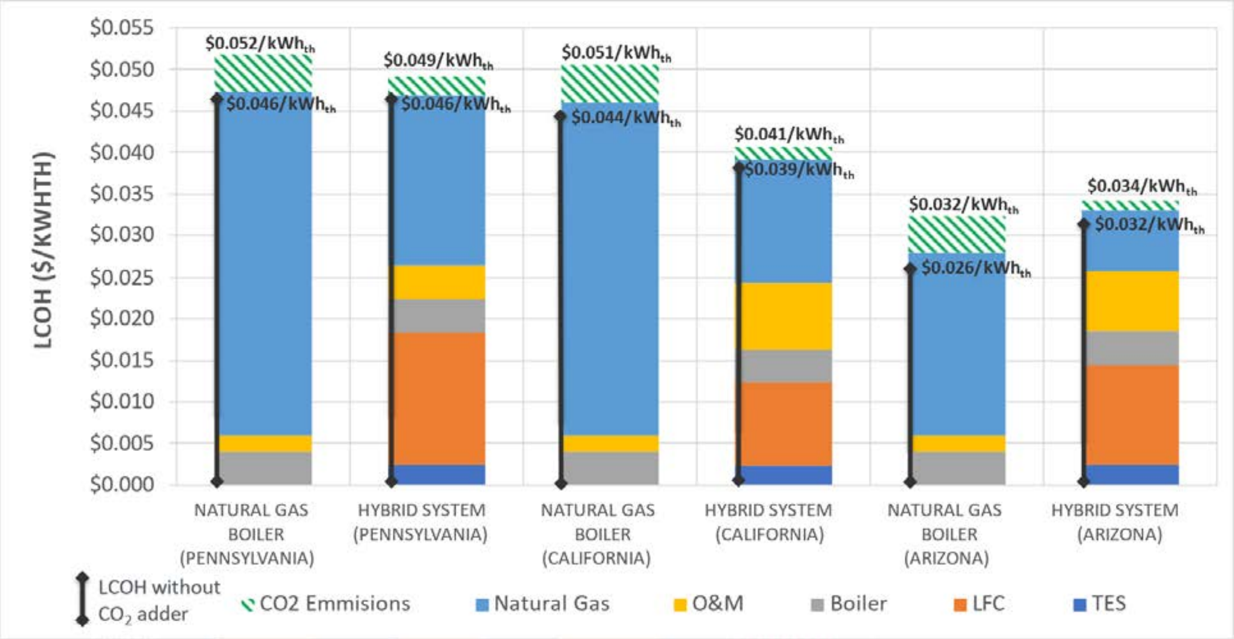
Levelized Cost of Heat (LCOH)

LCOH estimates for hybrid system case scenarios with CO_2 adder in;

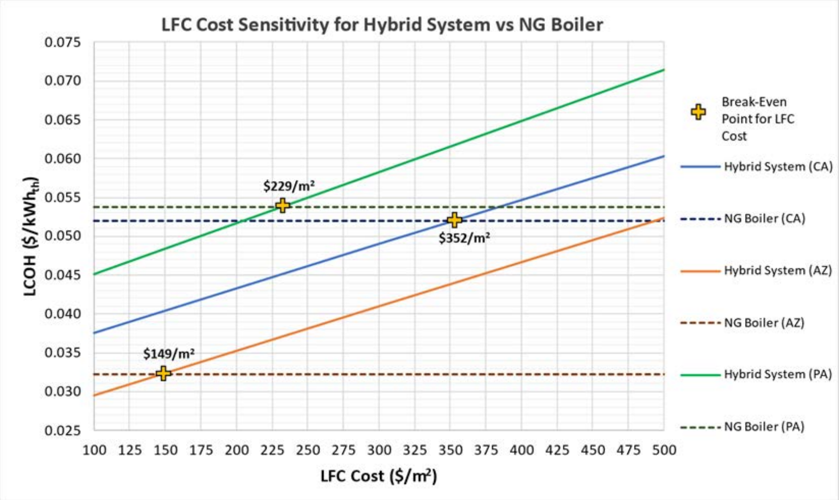
- <u>Pennsylvania</u>
  $0.049/kWhth with CO2 adder ($14.26/MMBTU)

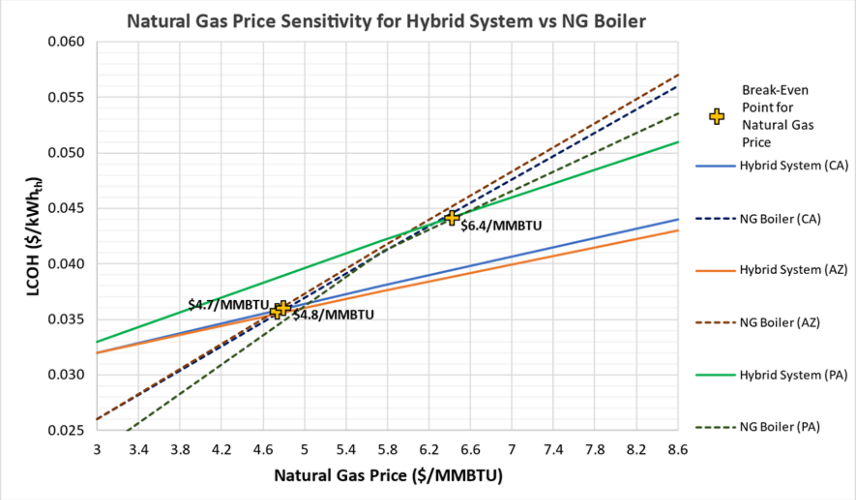
- <u>Arizona</u>
  $0.034/kWhth with CO2 adder ($9.85/MMBTU)

- <u>California</u>
  $0.041/kWhth with CO2 adder ($11.98/MMBTU)



Sensitivity Analysis





	LFC Price (With CO_2 adder) $/m^2	LFC Price (Without CO_2 adder) $/m^2	NG Price (With CO_2 adder) $/MMBTU	NG Price (Without CO_2 adder) $/MMBTU
PA	229	167	6.4	7.6
CA	352	267	4.8	5.9
AZ	149	76	4.7	5.8

- The hybrid system can be feasible for an LFC system cheaper that the break-even price in these states under the presented solar radiation, natural gas price, and the CO_2 tax.

5. Discussions & Future Work

Discussions

- The best-performing heat pump system uses solar concentrators to supply input heat, but this system does not achieve the lowest LCOH.
  - Installing a solar collector to provide input heat adds additional capital costs which increases the LCOH, meaning that the solar collector/heat pump system is not the most economic option.
  - The best LCOH can be achieved by a system that uses sewage waste heat as an input to the heat pump.

- Maximizing share of solar energy in the LFC-DSG hybrid system design is not the most feasible solution for the industrial application due to high LCOH. Optimizing the hybrid system by the best mix of natural gas and solar (i.e., 50% NG – 50% Solar) would give a competitive LCOH, thus the hybrid system could be feasible with respect to a standalone NG boiler system or a retrofit application.

- To make this system more competitive with natural gas only boiler systems, the carbon price $17.71/metric ton added to the LCOH calculation based on California's Cap-And-Trade Program (ICAP, 2021).

- This hybrid system can also provide natural gas offset up to;
  - 4,096 MWh_{th} (757 tons of CO2) in Arizona,
  - 4,009 MWh_{th} (741 tons of CO2) in California,
  - 2,720 MWh_{th} (508 tons of CO2) in Pennsylvania.

Future Work

- We will continue to improve the LFC-DSG model by optimizing the system configuration and dispatch model.
- In addition to optimization, a series of sensitivity analysis are done including location, DNI, LFC solar field size, LFC installed cost, PCM thermal storage capacity, and natural gas boiler back-up size.
- We will investigate hybridization options for the HTHPs coupled with low concentrating solar power systems such as flat plate collectors (FPCs).
- We also investigate the capital cost considering economies of scale and learning in manufacturing, O&M cost and potential reductions, and system lifetime improvements.
- We are also investigating the revenue creating through industrial heat generation, which will lead to an annual cash flow, and we would be able to calculate the payback period and internal rate of return for both greenfield hybrid system and retrofit applications.

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Thank You

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Financial Model Inputs

- Natural gas price is one of the key parameters that makes the Hybrid system feasible or unfeasible. We used 2020 average Industrial Natural Gas Prices and conversions for U.S., Arizona, California, and Pennsylvania (EIA, 2021a, 2021b) in the financial model.

	2020 Natural Gas Industrial Price ($/Mcf)	2020 Natural Gas Price ($/MMBTU)	2020 Natural Gas Price ($/kWh$_{th}$)
United States Average	3.29	3.17	0.011
Arizona	3.98	3.84	0.013
California	7.64	7.37	0.025
Pennsylvania	7.91	7.63	0.026

- The model is designed to optimize the solar field size and the thermal storage capacity to meet competitive LCOH. The summary of financial key inputs including the LFC system unit cost, PCM TES system unit cost, NG boiler total cost, carbon price, system lifetime and discount rate for the LCOH

LFC System Cost ($/m^2)	PCM System Cost ($/kWh$_{th}$)	CO_2 Price* ($/metric ton)	1 MW$_{th}$ NG Boiler Cost ($)	O&M (% of CAPEX)	System Lifetime (years)	Discount Rate (%)
175	25	17.71	$250,000	5%	25	10%

Heat Load & Generation Profile for Arizona

Location / Solar DNI
Tucson, Arizona, 7.36 kWh/m²/day

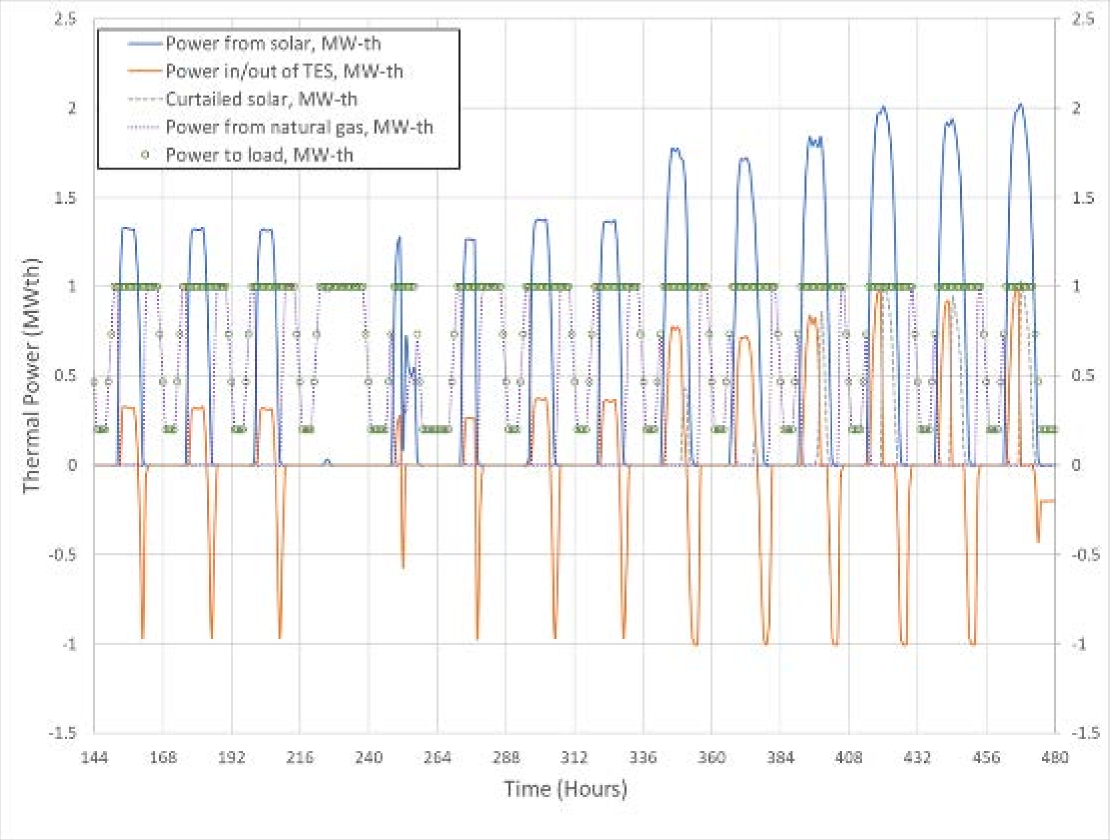
Heat Load
6am-8am: Ramping up to 0.47 – 0.75 MW_{th}
8am-10pm: 1 MW_{th} constant
10pm-12pm: Ramping down to 0.75 - 0.47 MW_{th}
12pm-6am: 0.2 MW_{th} constant

Natural Gas Price:
- $0.013 kWh/$3.38 MMBTU

PCM-TES Storage:
- 6 Hours

LFC Cost:
- 175 $/m²

PCM Thermal Storage System Cost:
- 25 $/$kWh_{th}$



Representative two-week timeline (one week from winter and one week summer) in California

Heat Load & Generation Profile for Pennsylvania

Location / Solar DNI
Pittsburgh Pennsylvania, 4.10 kWh/m^2/day

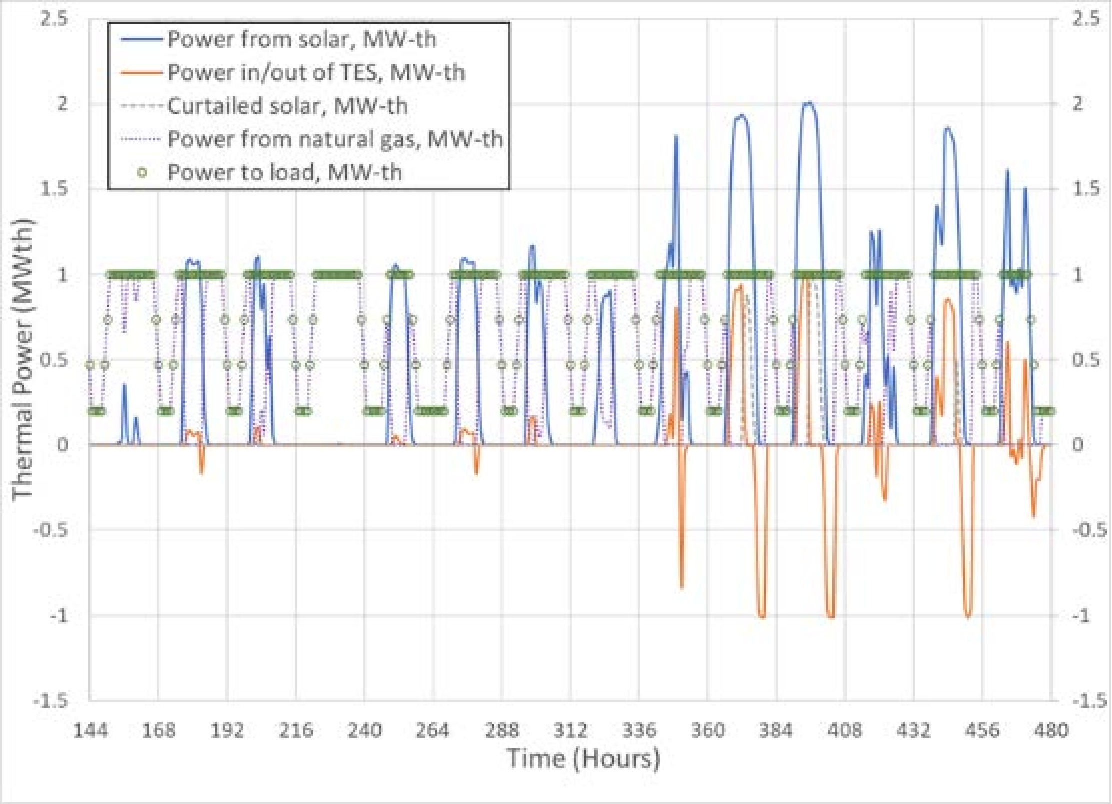
Heat Load
6am-8am: Ramping up to 0.47 – 0.75 MW_{th}
8am-10pm: 1 MW_{th} constant
10pm-12pm: Ramping down to 0.75 - 0.47 MW_{th}
12pm-6am: 0.2 MW_{th} constant

Natural Gas Price:
- $0.026 kWh/$7.63 MMBTU

PCM-TES Storage:
- 6 Hours

LFC Cost:
- 175 $/m^2

PCM Thermal Storage System Cost:
- 25 $/kWh$_{th}$



Representative two-week timeline (one week from winter and one week summer) in California