Small-Scale CSP Systems for Industrial Process Heat on Urban Brownfields

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Heliostat Consortium for Concentrating Solar-Thermal Power

Outline

- Overall Project Scope
- Test Case
- Additional Potential Use Cases
    - Heliostats in a Combined Cycle for Waste Heat Recovery
    - Even Smaller Scale Applications: Solar Thermal-Boosted Organic Rankine Cycle
- Conclusions

Acknowledgements

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- Co-PI James Elliott (Sociology)

- Energy Systems Lab Students






Overall Project Scope: Introduction

Why is Industrial Process Heat So Important?

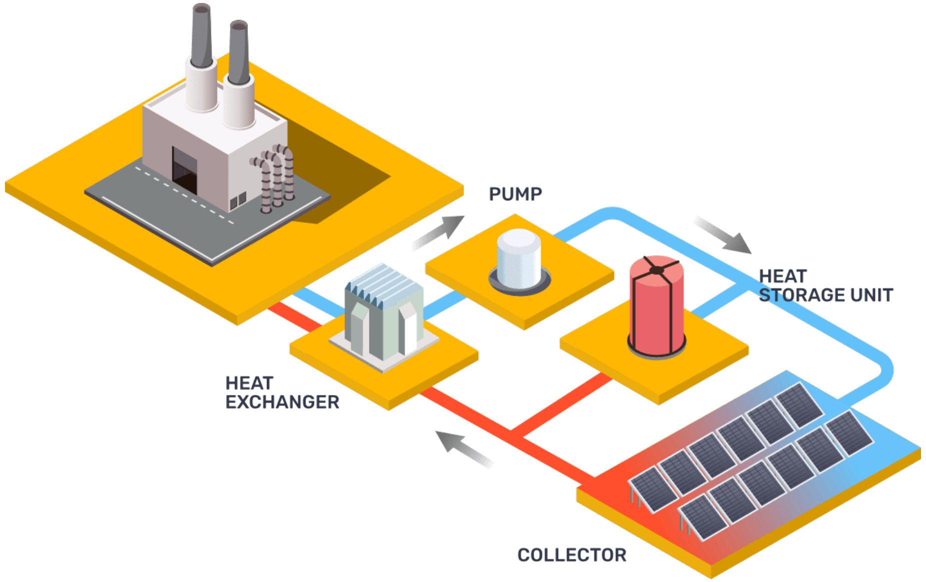
High Industrial Energy Demand
Industry accounts for ~38% of global final energy use

Industrial Process Heat (IPH)
Over 50% of U.S. manufacturing energy goes to process heat; globally IPH forms ~20% of energy demand

Urgency of Supply
Global IPH demand may grow 17% by 2030, requiring renewable heat solutions to meet these needs

Why Concentrated Solar Thermal (CST) and Solar IPH?

- **Improving Energy Independence:** Solar IPH reduces reliance on imported fuels.
- **High-Temperature Capability:** CST can supply high-temperature heat (100–1000°C) essential for diverse industrial processes.
- **Renewable and Dispatchable:** CST coupled with Thermal Energy Storage (TES) can deliver stable, dispatchable heat even when solar resources fluctuate.
- **Economic Potential:** CSP systems can achieve competitive Levelized Cost of Heat (LCOH), especially in regions with strong solar resources and rising fuel prices.
- **Small-Scale Modular Systems:** Compact CSP installations (≤5 MW) can be strategically deployed near industrial consumers.



Schematics of solar industrial process heat system. Source (s): Bees Group.

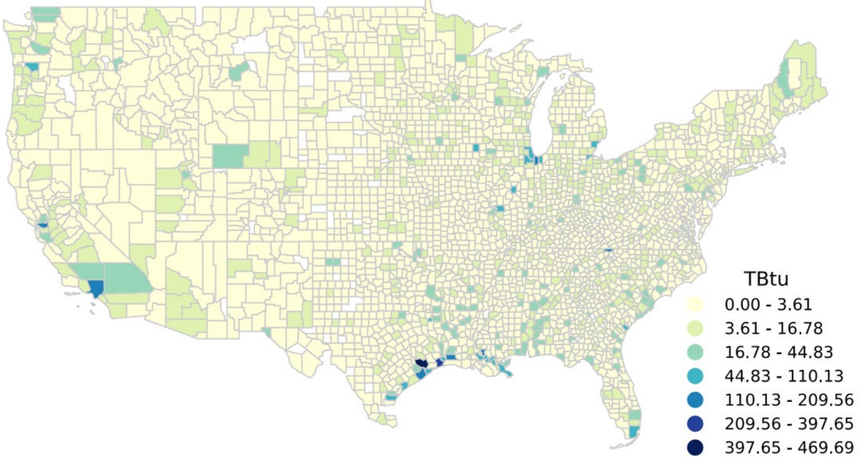
Why Urban Brownfields for CST Deployment?

- **Underutilized Land:** Urban brownfields are former industrial sites, often contaminated and unused, presenting opportunities for redevelopment into productive energy sources.
- **Proximity to Industrial Demand:** Brownfields are frequently located near industrial zones, aligning CST heat production directly with the end-use industrial processes.
- **Lower Remediation Costs:** Redeveloping brownfields involves less stringent remediation compared to residential or commercial reuse, reducing cleanup costs and duration.
- **Local Community Benefits:** CST deployment will help economically revive adjacent communities, creating local employment opportunities and enhancing resilience.
- **Reduction of Pollution Risks:** Redeveloping brownfields with clean CST technology reduces further pollution, benefiting areas with historically high exposure to industrial contaminants.

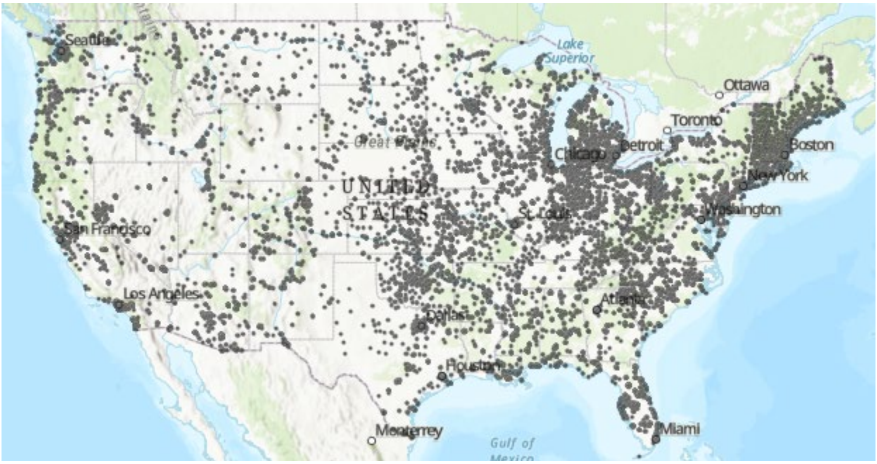
Houston brownfields. Source (s): houstontx.gov, Houston Public Media

How Does This All Come Together?

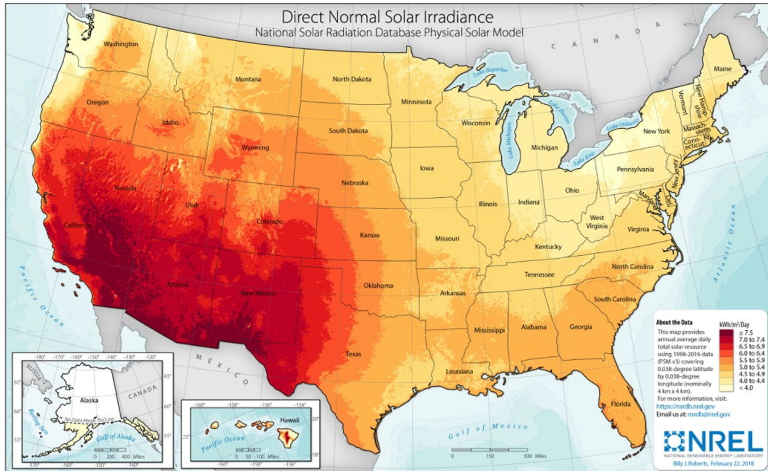
IPH Demand by Level and County



Brownfield Locations



DNI Levels

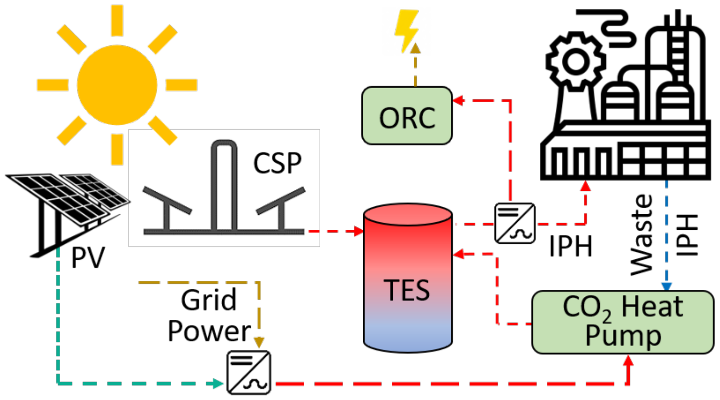


Overall Approach

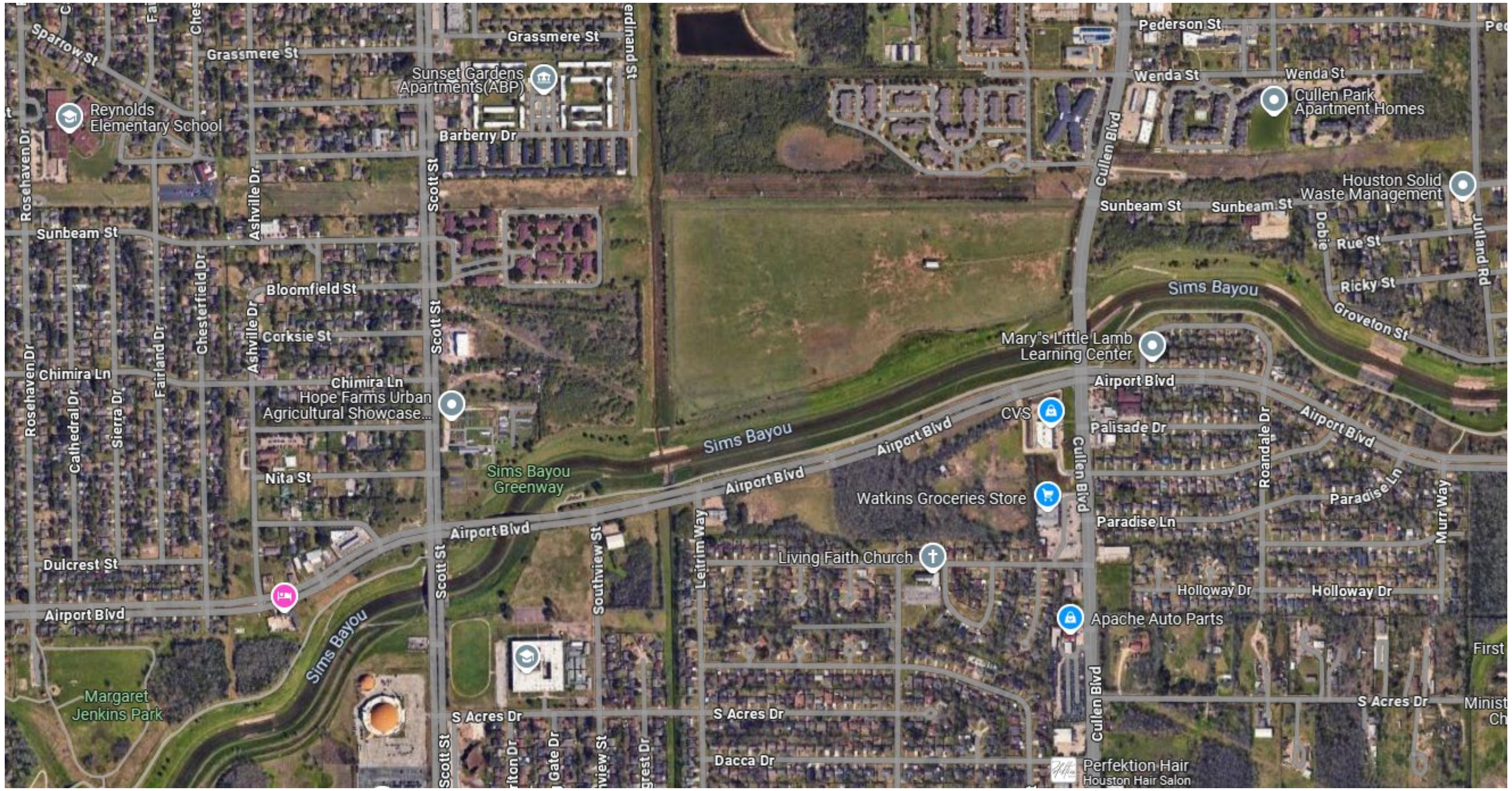
- Quantify heliostat field potential for smaller-scale footprints (~10, 30, 50 acres)
- Investigate combined field-cycle installations
- Map these results to actual brownfield locations with adjacent or nearby IPH needs

IPH Demand By Temperature Range

Temperature Range	Value
< 100°C	33%
100–500°C	44%
500–1000°C	13%
> 1000°C	9%

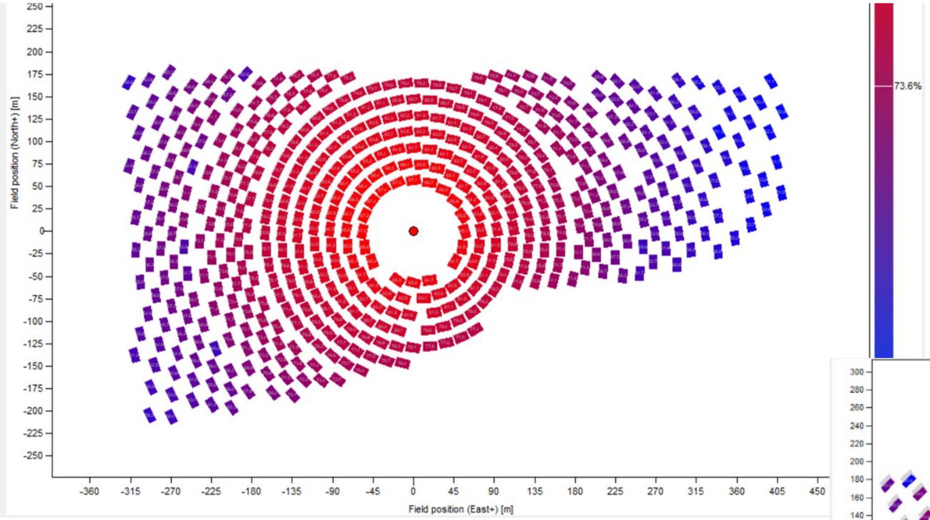


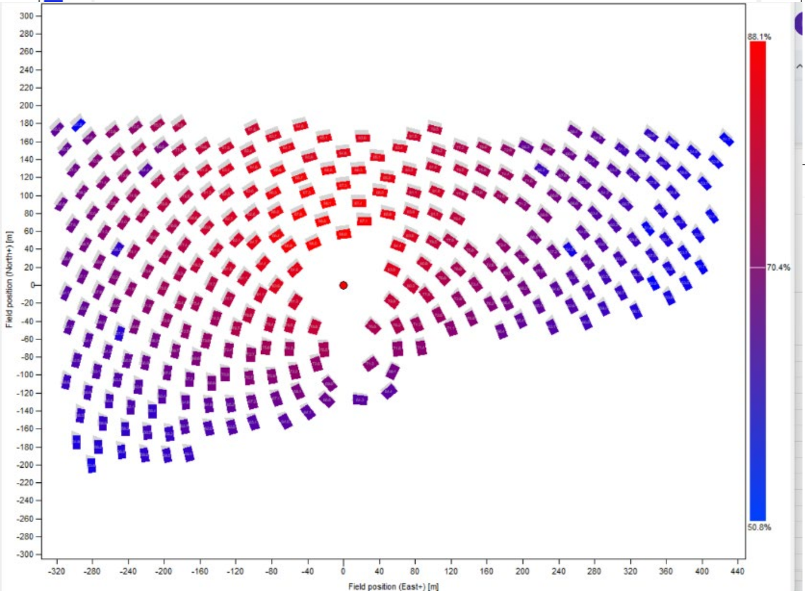
Example Site Installation

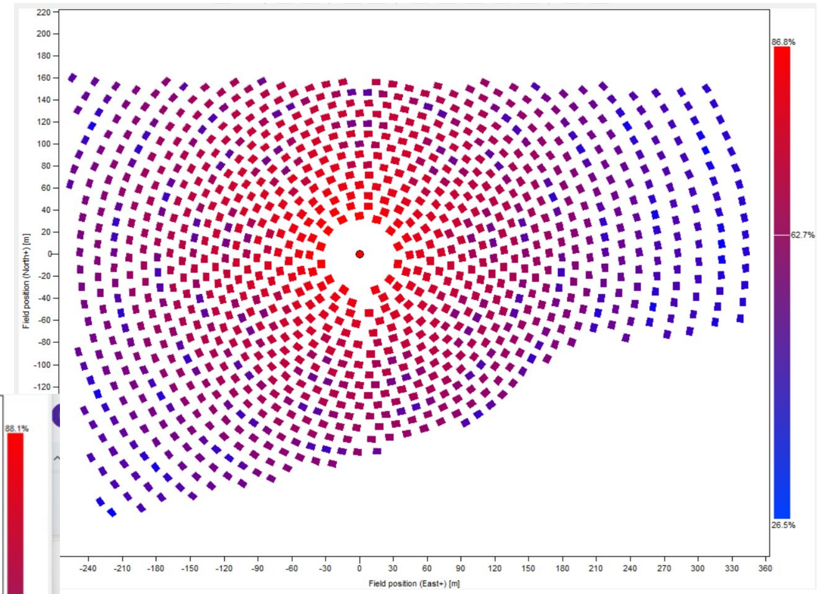


~50 acres

Many Potential Field Configurations







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Material and Construction Cost Reductions

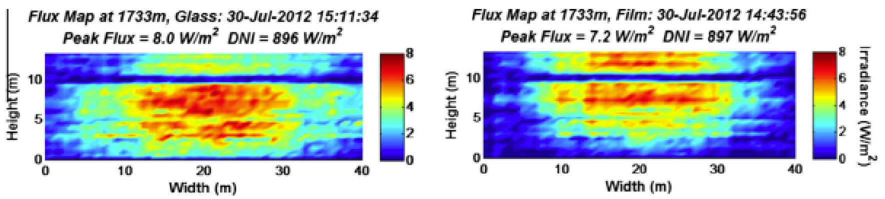


Fig. 9. Measured irradiance distribution at ~1700 m from the silvered glass facet (left) and the SMF1100 facet (right). The peak flux in both cases is ~7–8 W/m².

Fig. 1. Left: heliostat 12W14 at the NSTTF in Albuquerque, NM, which was retrofitted with 3M™ Solar Mirror Film 1100. Right: NSTTF heliostat field with location of 12W14 heliostat circled.

3M Reflective Film
https://doi.org/10.1016/j.solener.2013.06.015

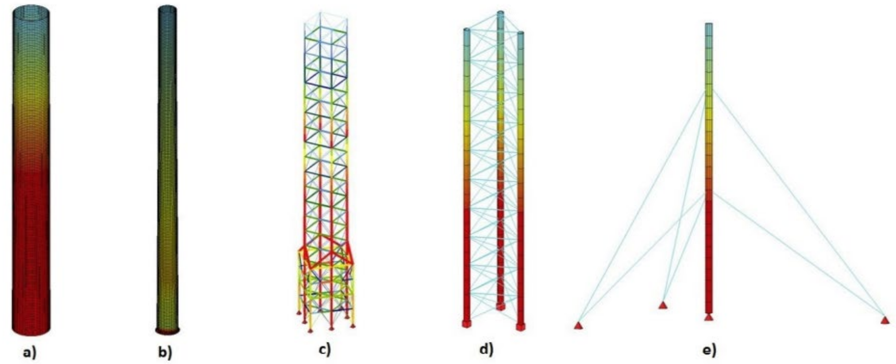


FIGURE 3. FE-models of investigated tower designs: a) concrete tube, diameter 22 m; b) concrete tube, diameter 15 m; c) lattice steel tower with socket; d) three-leg hybrid tower with concrete columns and steel bracings; e) cable-stayed concrete tube with two layers of cables

Tower Design
https://doi.org/10.1063/1.5067098

Combined Cycle Configurations

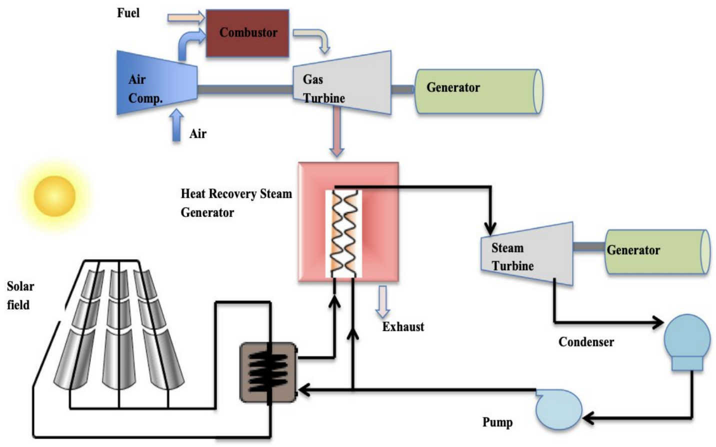
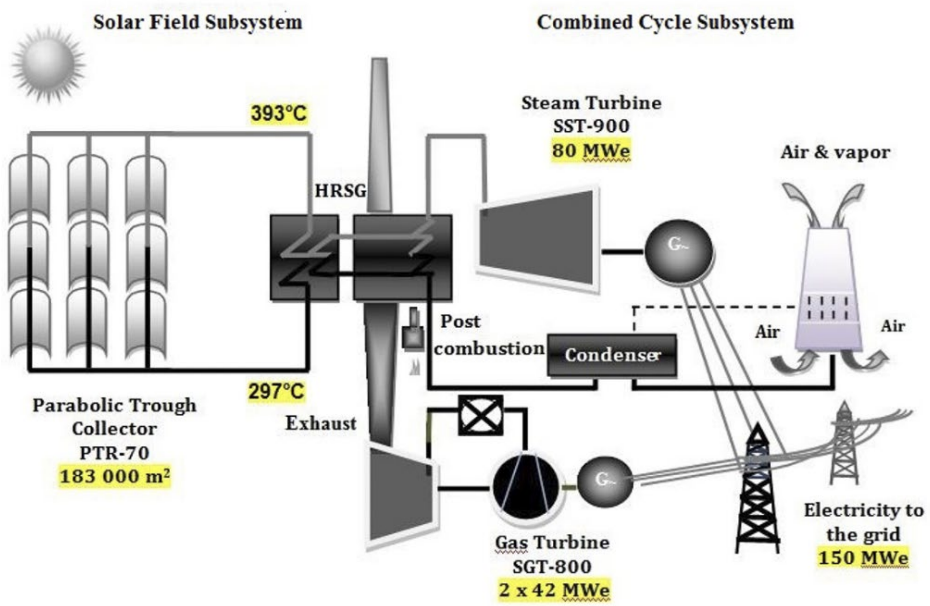


Fig. 1. Diagram of an ISCC plant.



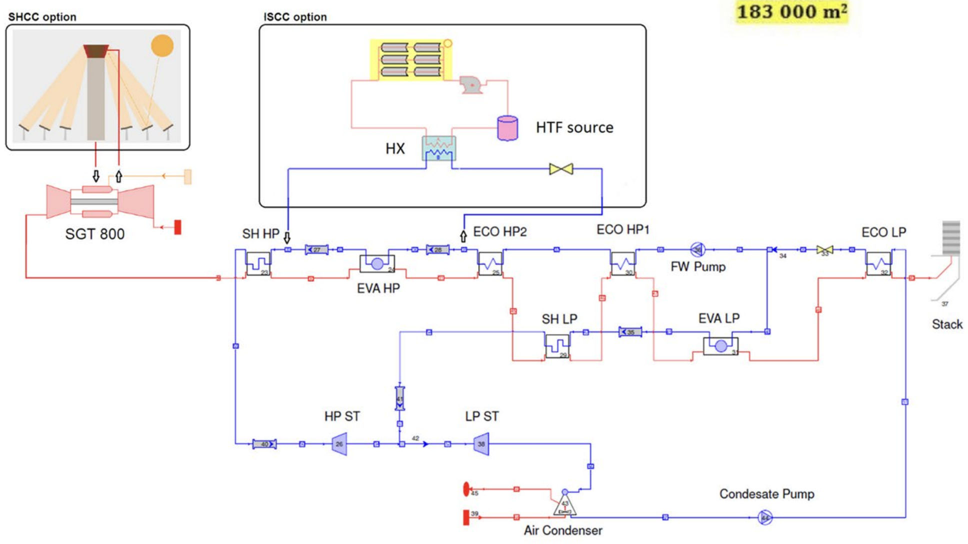


Fig. 1 Schematic of the investigated solar-fossil combined cycle: ISCC versus SHCC option

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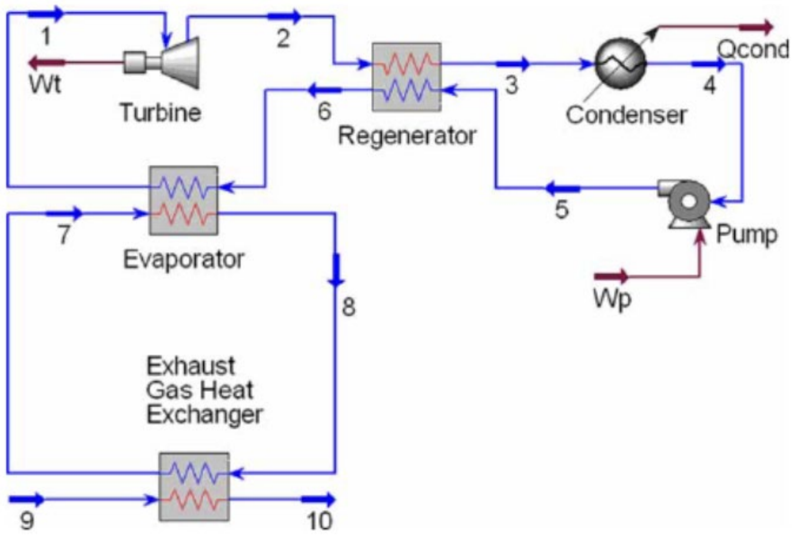
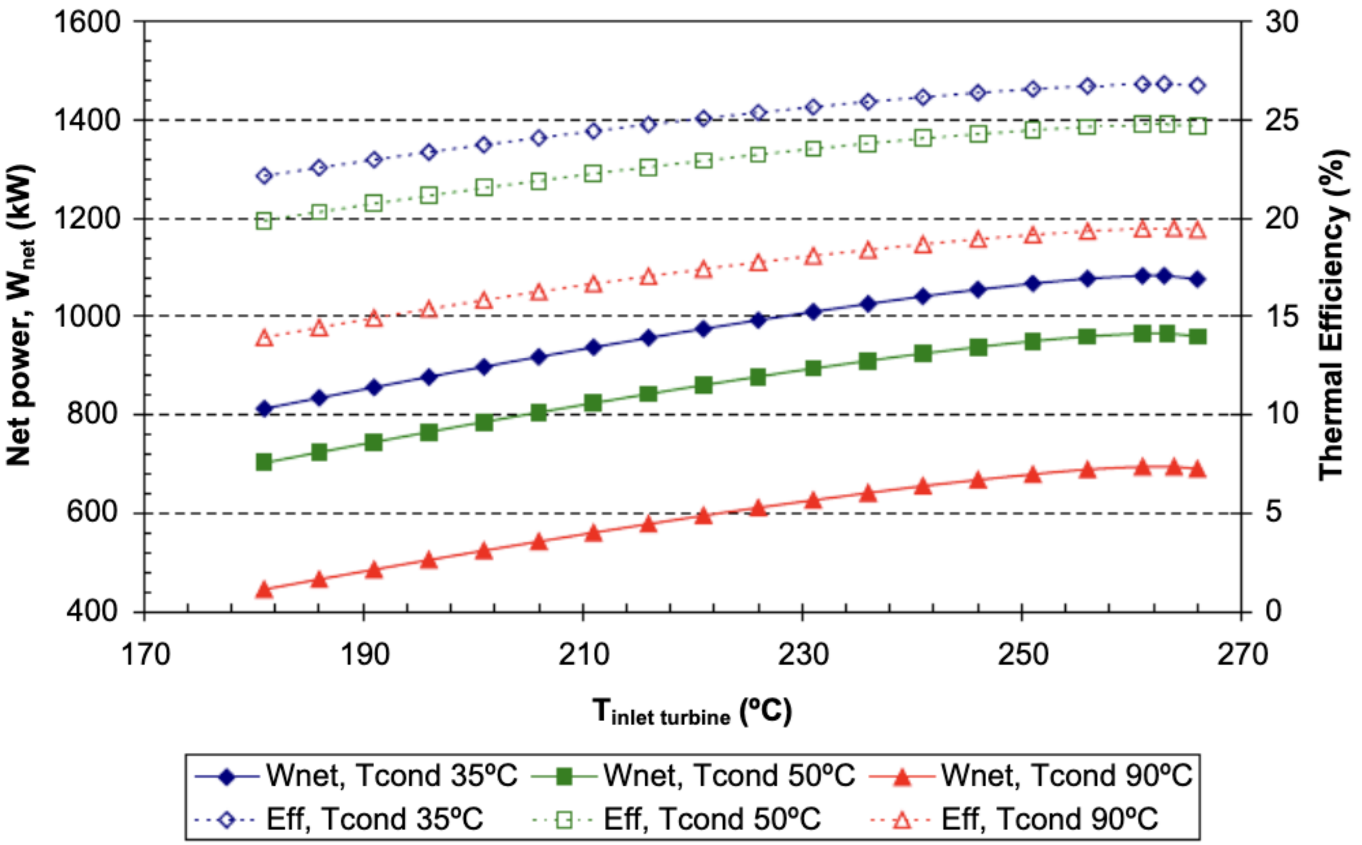
Combined Cycle Configurations: ORC

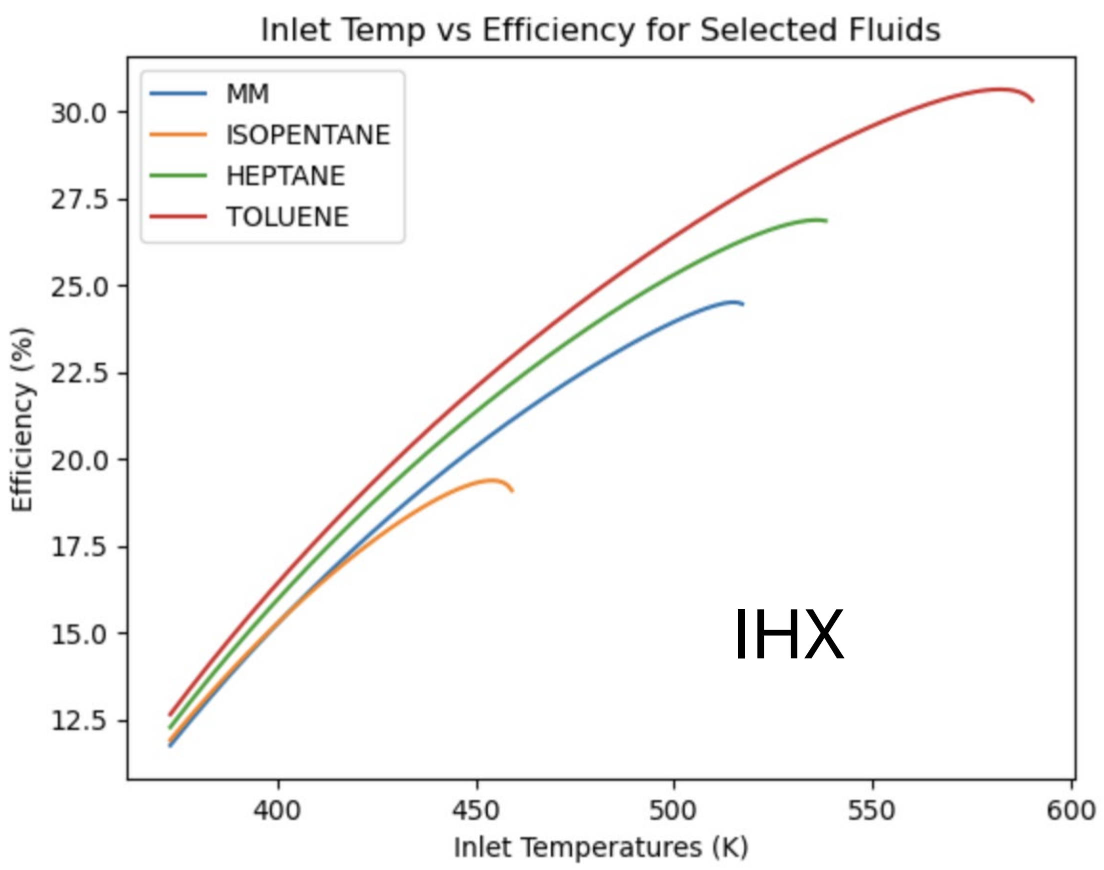
- Combined cycle simulatioı n-Heptane, ORC with IHX

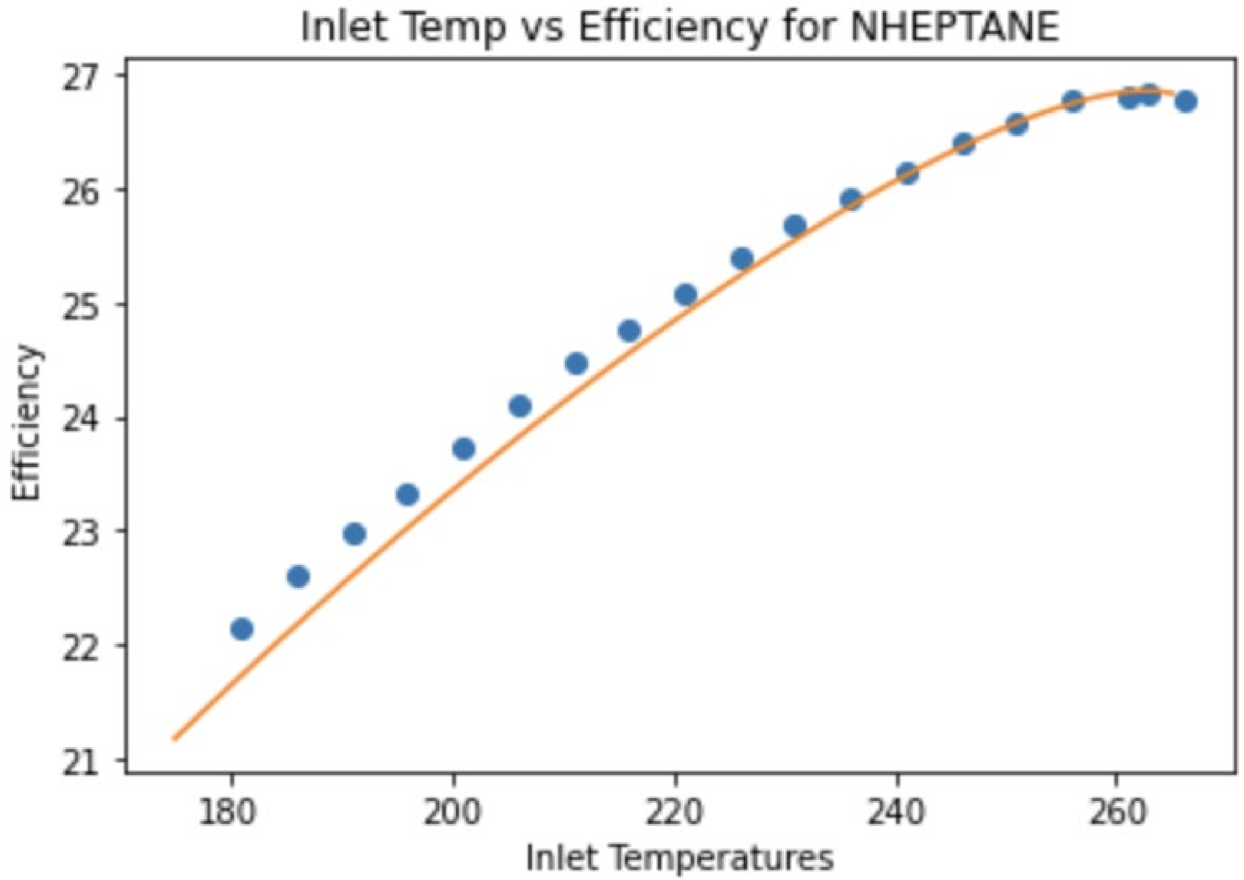




https://www.researchgate.net/publication/245392690_Thermodynamic_Optimization_of_Organic_Rankine_Cycles_at_Several_Condensing_Temperatures_Case_Study_of_Waste_Heat_Recovery_in_a_Natural_Gas_Compressor_Station

ORC Analysis



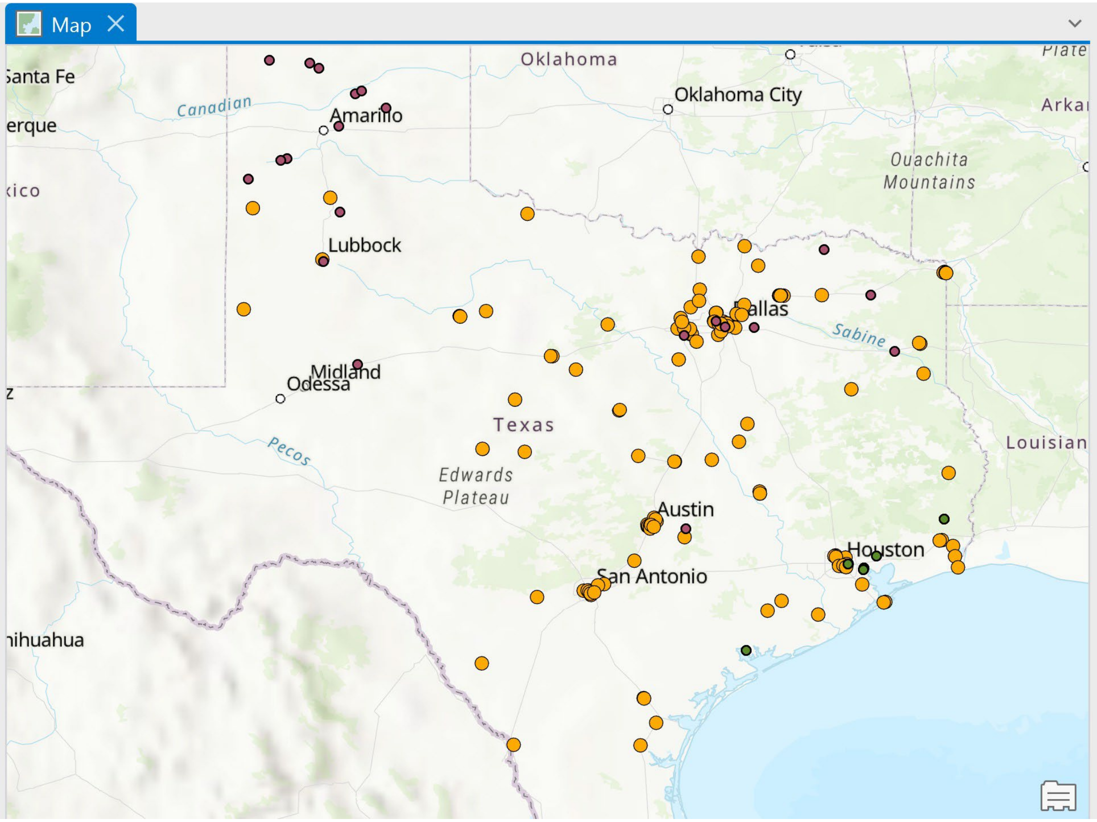


GIS Visualization

- Combining DNI map, STEP1 IPH information, national and local catalogs of brownfield locations
- Consulting with local/regional groups for input

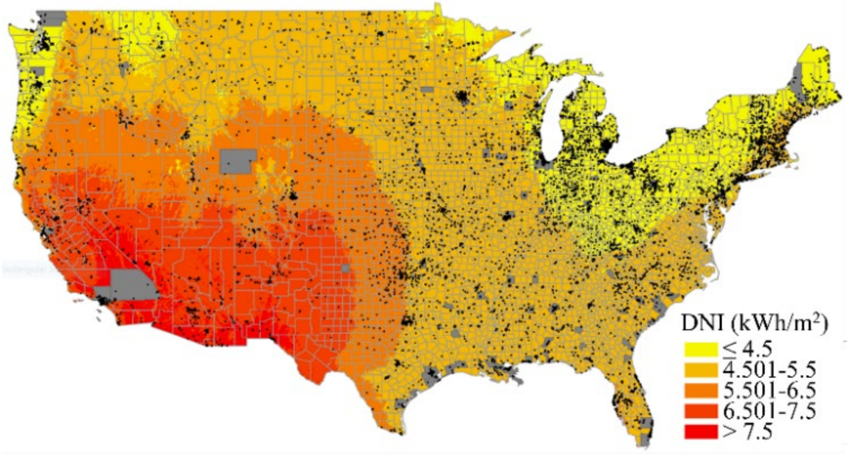
Brownfields - Brownfields

SHAPE	Point
OBJECTID	159435
REM_PROG	Brownfields Site Assessment (BSA)
RN	RN100521053
BSA_ID	G038
SITE_NAME	HOMESTEAD PLAZA SHOPPING CENTER
PHYS_ADDR	9929 HOMESTEAD RD
ADDR_DESC	NEAR SWC OF HOMESTEAD RD AND PARKER RD
CITY	HOUSTON
COUNTY	HARRIS
ZIP_CODE	77016
REGION	REGION 12 - HOUSTON
LAT_DD	29.856051
LONG_DD	-95.301436
HORZ_METH	DOQ
HORZ_ACC	5
HORZ_REF	FAC_CEN
HORZ_DATE	20010611
HORZ_ORG	TCEQ
HORZ_DATUM	NAD83
HORZ_DESC	Null



Test Case Methodology: Modeling and GIS Integration

- **Simulation Model:** NREL's System Advisor Model to evaluate technical and economic performance.
- **GIS Integration:** Combined solar irradiance, IPH demand, and brownfield data to identify feasible urban deployment sites.
- **Three Scenarios Modeled:** 5-MW_t each
  - Parametric analysis of solar multiple (SM) and TES capacity
  - Location: Houston, TX

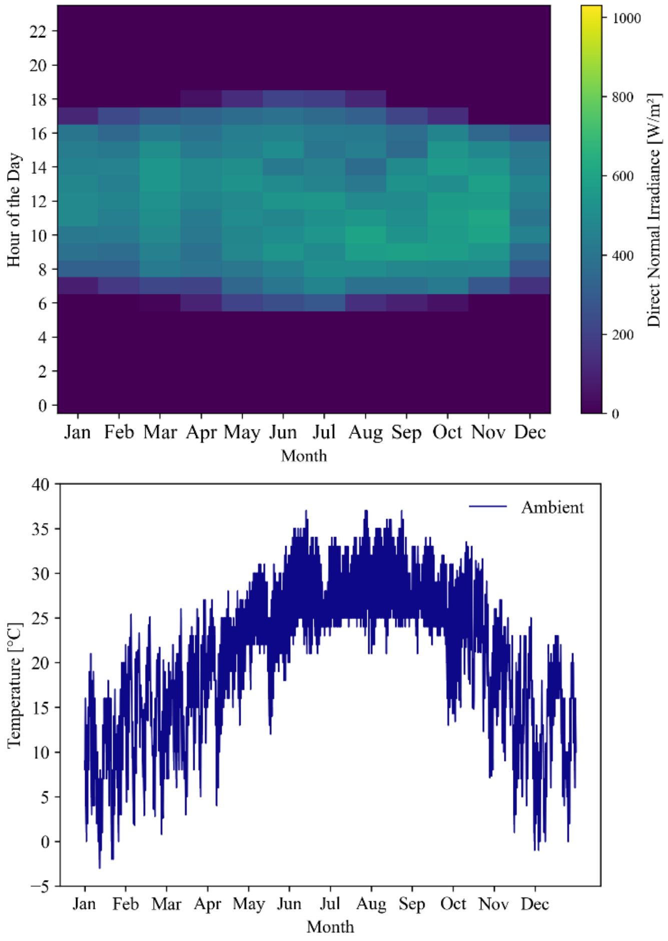


GIS map highlighting brownfields (black dots), IPH demand ≥ 24 TBtu (by county, gray), and DNI levels

Simulated IPH cases – 5 MW_t

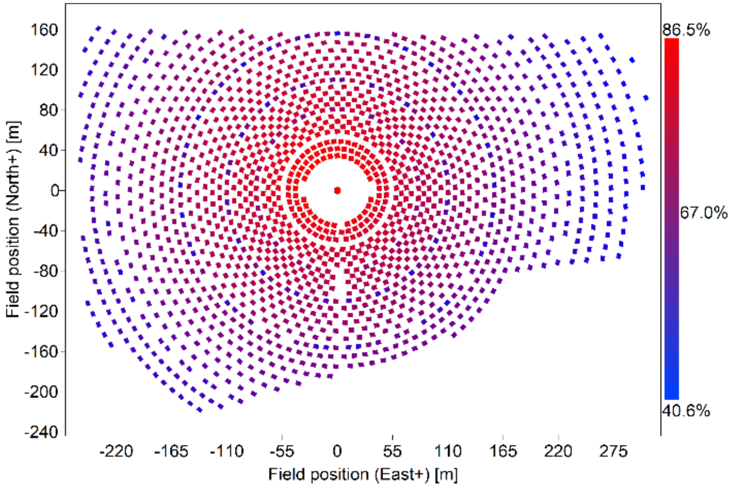
IPH Scenario	Supply Temperature	CSP Technology
Low Temperature	150°C	PTC
Medium Temperature	300°C	PTC
High Temperature	574°C	MSPT

Case Study: Houston, TX



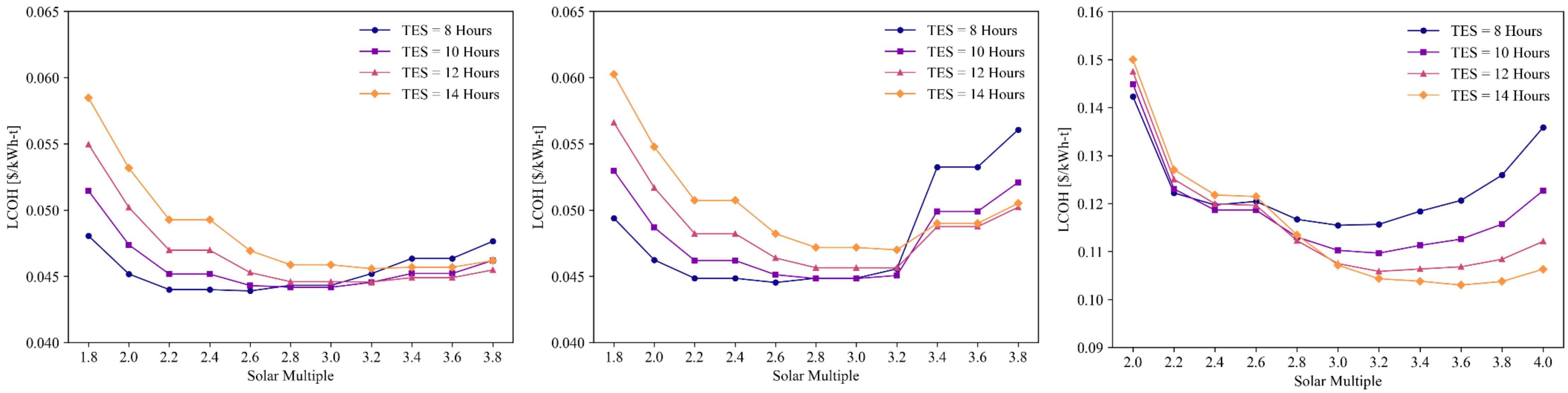
Direct normal irradiance (top) and ambient temperature (bottom) in Houston, TX

Selected brownfield located in Sunnyside, Houston, TX



SolarPILOT optimized heliostat field for MSPT

Parametric Analysis: SM vs TES



Parametric optimization of solar field (SM) and TES sizing. PTC-150°C (left), PTC-300°C (center), and MSPT-574°C (right).

Optimal Scenario (Minimum LCOH)

- PTC: SM is 2.6 and TES is 8
- MSPT: SM is 3.6 and TES is 14

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Economic Analysis

$$LCOH = \frac{FCR\ x\ TCC + FOC}{AHP} + VOC$$

LCOH = Levelized Cost of Heat ($/kWht)
FCR = Fixed Charge Rate
TCC = Total Capital Cost
VOC = Variable Operating Cost ($/kWht)
FOC = Fixed Operating Cost ($)
AHP = Annual Heat Production (kWht)

Parameter	Value
Analysis Period	20 Years
Variable Operating Cost	0.001 $/kWh_t$
Inflation Rate	2.5%
Contingency	7%
Nominal Debt Interest Rate	7%
Site Improvement	16 $/m^2$

Results: Techno-Economic Evaluation

PTC Cases

- Both PTC plants are economically feasible and exhibit similar performance.
- Slightly better output and economics at lower temperatures.

MSPT Case

- Provides higher temperature capability (574°C), but significantly higher LCOH, making it economically less attractive.
- Requires a substantially larger capital investment and land area compared to PTC.
- Higher annual thermal output and a better capacity factor but is overshadowed by cost.

All configurations significantly reduce annual carbon emissions, contributing effectively toward industrial decarbonization goals.

Performance comparison

Parameter	PTC 150°C	PTC 300°C	MSPT 574°C
Annual Energy (MWh_t)	20,092.25	19,749.53	23,192.37
Capacity Factor (%)	45.9	45.1	53
Thermal Storage (Hours)	8	8	14
Capital Cost (M$)	11.07	11.07	25.53
LCOH (¢/kWh_t)	4.39	4.45	10.30
Land Required (Acres)	16	16	35.77
Annual Carbon Avoided (Metric Tons)	11,478	11,282	13,248

Opportunity and Challenges

- **Economic Potential of Small-Scale:** Parabolic trough collectors (PTCs) demonstrate strong feasibility for lower-temperature industrial heat applications, highlighting an immediate opportunity for deployment.
- **Cost Challenges for MSPT:** MSPT technology shows high thermal performance but faces economic hurdles at smaller scales due to high LCOH.
- **New Cost Models:** Current economic models (e.g., SAM) require improved cost curves tailored specifically for modular, small-scale CST systems, especially for MSPT technology.
- **Scaling CSP/CST Systems:** Transitioning from large-scale to modular CSP/CST introduces new complexities in construction, logistics, and economics that require focused research and innovation.
- **Brownfields:** Accurate cost estimation incorporating land cost, site-specific remediation, and preparation costs, along with potential financial support from government programs is a challenge.

Sensitivity Analysis: MSPT Cost

Impact of Heliostat Cost

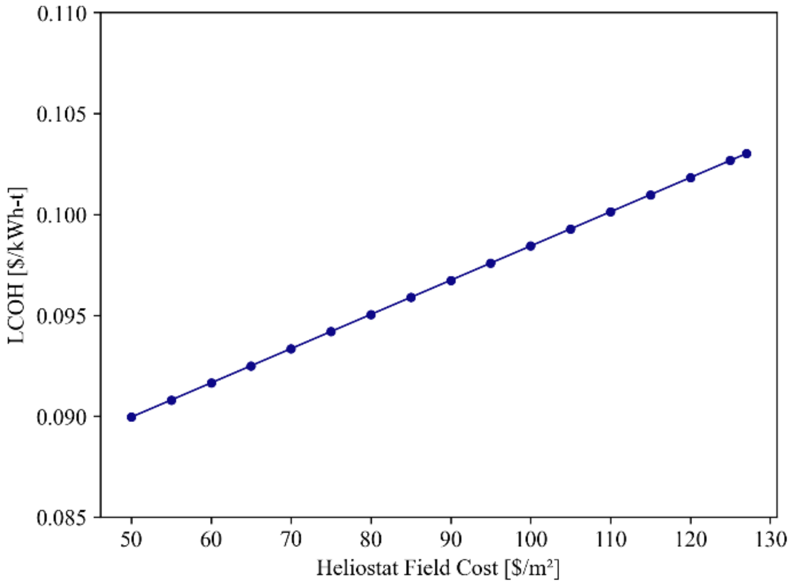
- Heliostat cost significantly influences the overall economic viability of MSPT plants.
- 17% of the total installed cost.
- SAM's current default heliostat cost is 127 $\$/m^2$
- U.S. DOE's heliostat cost target (50 $\$/m^2$) reduces LCOH but still results in higher costs compared to PTC configurations.

Dominance of Receiver and Tower Costs

- Receiver and tower components comprise ~48% of MSPT cost.
- Highlighting the need for new cost models tailored to smaller-scale CSP systems.

Solution

- Development of accurate cost scaling factors for heliostats, receivers, and towers at small scales.



Sensitivity analysis for heliostat field cost. Maximum is the current SAM cost, while minimum is the DOE target heliostat cost.

Conclusion and Future Work

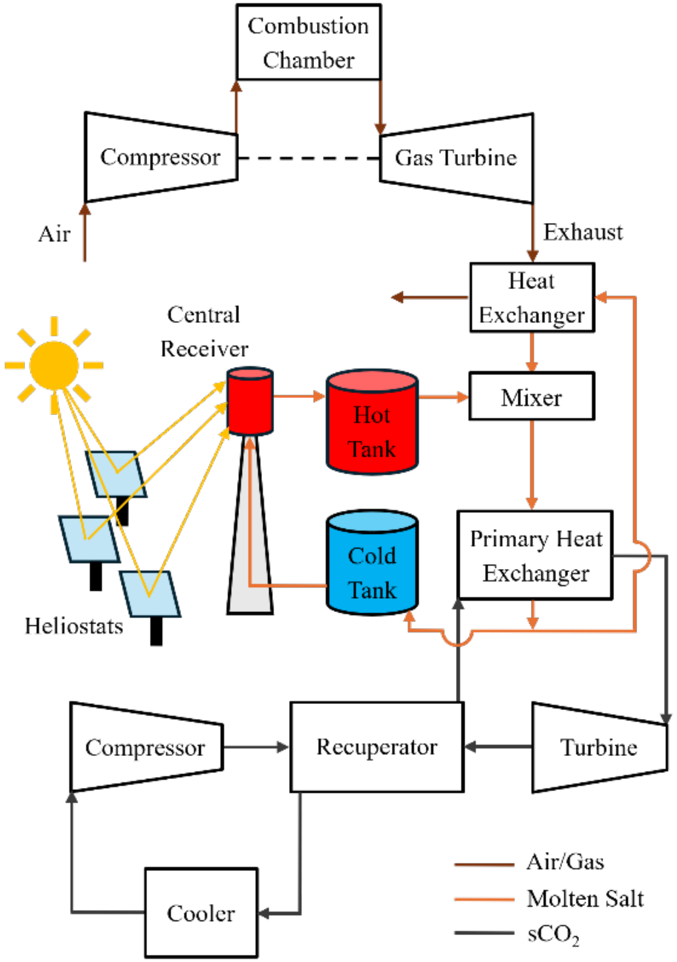
- Small-scale CST using PTC is economically viable for low to medium temperature IPH (150°C and 300°C), with competitive LCOH.
- MSPT (574°C) system, although thermally viable, is economically challenging due to high capital cost.
- Deploying CST on urban brownfields could optimize land use, reduce pollution impacts, and economically revitalize local communities.

Moving Forward

- Development of accurate cost models specifically for modular, small-scale CSP applications.
- Detailed analysis of brownfield remediation costs and potential government incentives.
- Exploration of combined heat and power (CHP) integration to enhance system economics and performance.
- Broader geographic and technical feasibility studies to support widespread adoption.

Additional Use Cases: Example 1, Hybrid WHR System

- Primary Components
  - Gas Turbine
  - Molten Salt Power Tower
  - Thermal Storage
  - sCO_2 Brayton Cycle
- GT exhaust heats molten salt via a WHR heat exchanger.
- Mixed salt (from TES & WHR) drives the sCO_2 power block.
- Can operate in solar-only mode for flexibility.



Schematics of the proposed CSP-sCO_2 hybrid WHR system

Components

Gas Turbine Power Plants

- Gas turbines (GTs) emit high-temperature exhaust (>500°C).
- Large amount of waste heat.

Hybrid WHR

- Renewable integration enhances energy independence as well as flexibility.
- Concentrated Solar Power (CSP) suitable for GT exhaust integration.
- Higher efficiency, lower emissions, and costs.

Concentrated Solar Power

- Can reach high temperatures similar to GTs.
- Thermal energy storage (TES) – Dispatchable.

Modeling Framework

A comprehensive techno-economic model.

Python-based model: GT, sCO_2, and CSP components

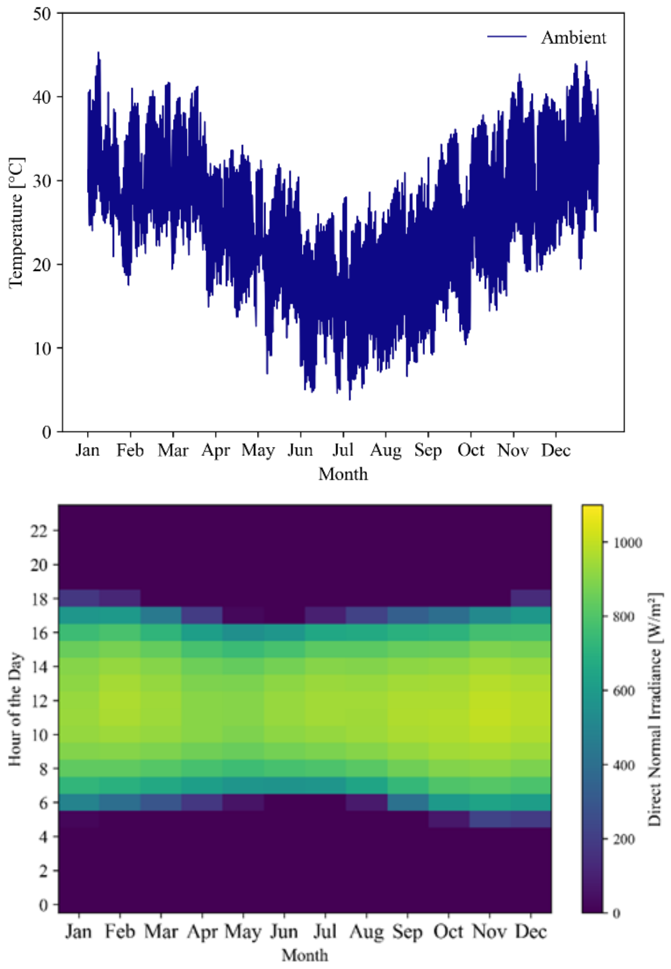
SolarPILOT for solar field layout optimization

PySAM for CSP components

sCO_2 model for power cycle with GT waste heat integration

Case Study (Newman, WA)

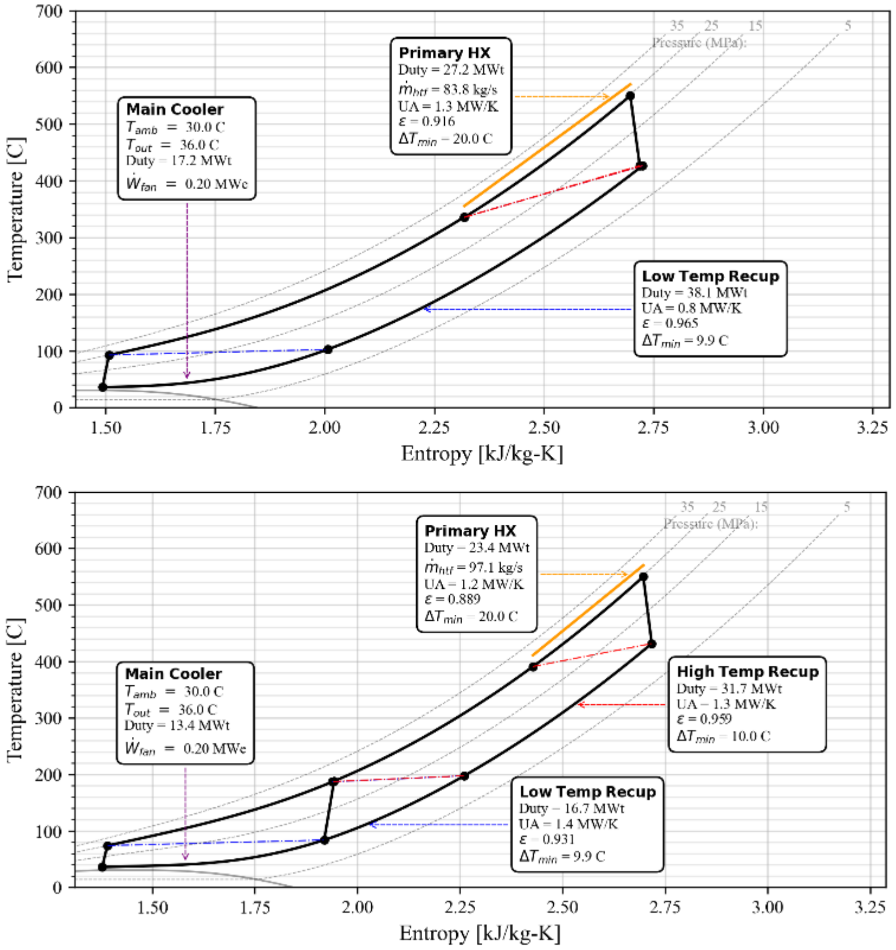
- GTs are primarily used for power in the Australian mining industry.
- Mining sites use open-cycle GTs off-grid and in remote areas.
- Rising gas prices are a major concern.
- These locations have very high solar resource for CSP deployment.
- Newman in Western Australia is one such location



Ambient temperature (top), direct normal irradiance (bottom) in Newman, WA

Results: sCO_2 Power Cycle

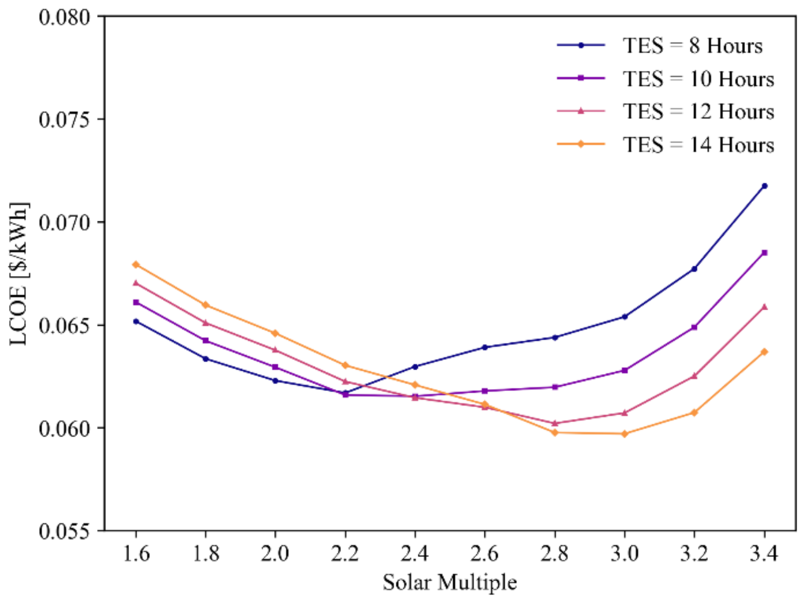
- Capacity = 10 MWe
- Design efficiency
  - Simple = 36.8%
  - Recompression = 42.7%
- Recompression cycle is selected due to higher efficiency.

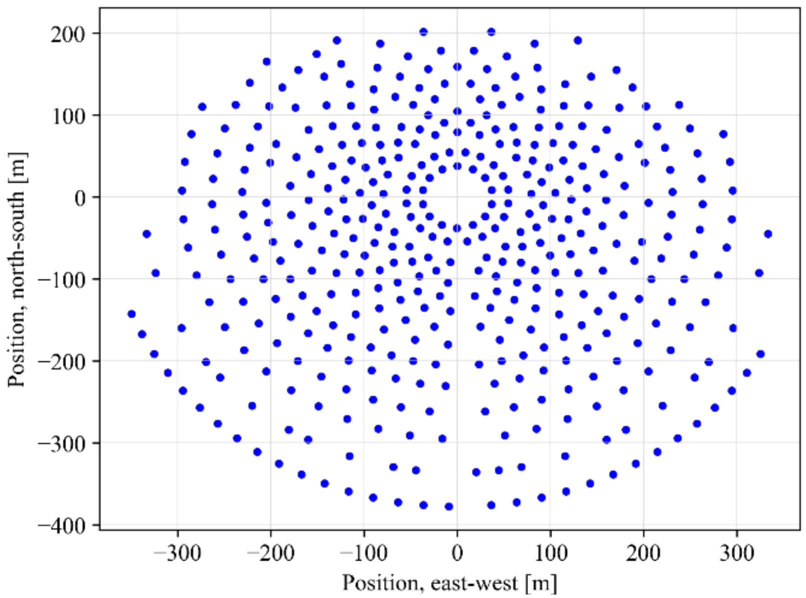


T-S diagram for sCO_2 cycle, simple (top), recompression (bottom)

Results: Molten Salt Power Tower – CSP Component

- Solar field capacity = 30 MWt
- Thermal storage capacity = 14 hours





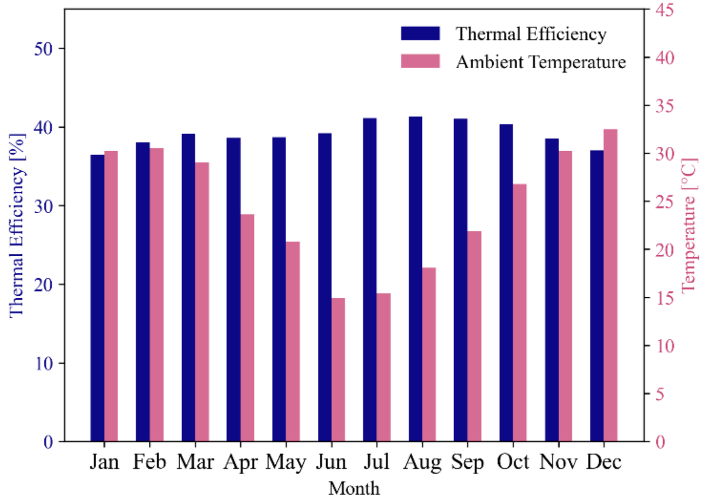
Thermal storage and solar field sizing (left), SolarPILOT optimized solar field layout (right)

Results: Techno-Economic Evaluation

- Output: 56,028.78 MWh/year, LCOE = \$0.0597/kWh.
- Average sCO_2 efficiency = 39%.
- CSP = largest cost share → field/TES optimization critical.
- 29% cheaper LCOE vs CSP–Rankine (0.0843 → 0.0597 \$/kWh).

Techno-economic evaluation

Parameter	Value
Annual Production (Electricity)	56,028.78 MWh
Mean Power Cycle Efficiency	39%
LCOE	0.0597 \$/kWh
CSP Cost	36.78 M\$
sCO_2 Cycle Cost	18.27 M\$
Net Capital Cost	55.74 M\$



Monthly power cycle efficiency and ambient temperature

Comparison with Standalone CSP-Rankine

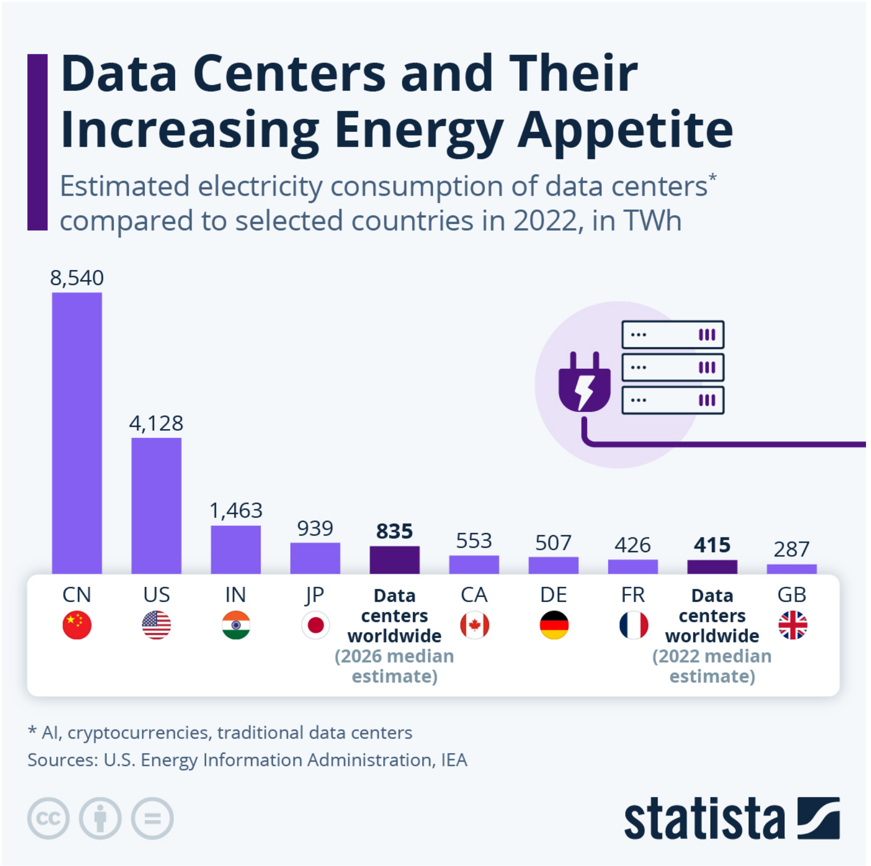
Parameter	CSP-sCO_2 WHR	Standalone CSP-Rankine
Nameplate Capacity	10 MWe	10 MWe
Mean Power Cycle Efficiency	39%	34.24%
LCOE	0.0597 \$/kWh	0.0843 \$/kWh
SM	3	3
TES	14 Hours	14 Hours
Net Capital Cost	55.74 M\$	101.76 M\$

Example 2, Solar Thermal-Boosted Organic Rankine Cycle for Data Centers

Rising Technology
The rise in technology has led to an exponential increase in the number of data centers.

Growing Electricity Demand
Data centers are consuming more power than some countries.

Waste Heat Dissipation
A significant amount of the consumed power is lost as waste heat due to the cooling mechanism.



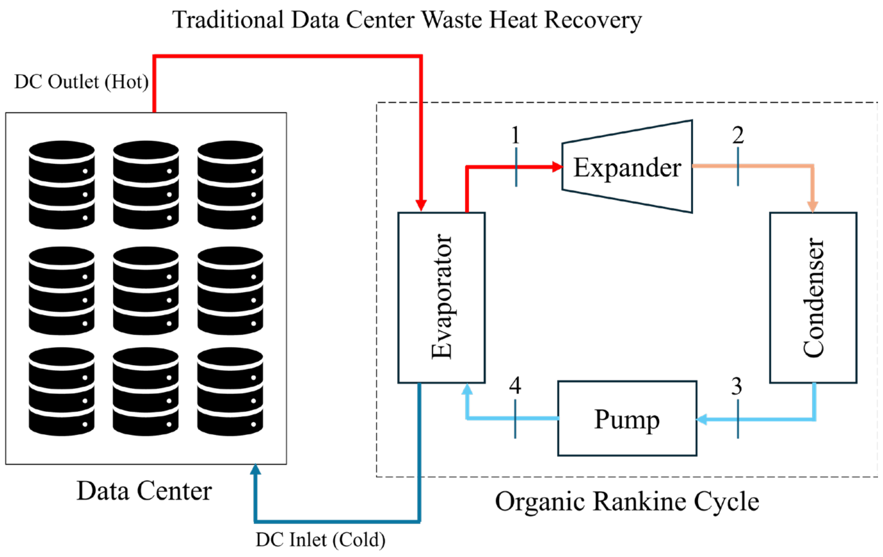
Data Centers & Waste Heat Recovery (WHR)

Opportunity

- Untapped potential
- Significant energy efficiency gain
- Existing technology such as the organic Rankine cycle (ORC)

Challenges/Drawbacks

- Waste heat typically 40–60°C: hard to recover
- Low ORC supply temperatures
- Low ORC thermal efficiency
- High cost (levelized cost of electricity)



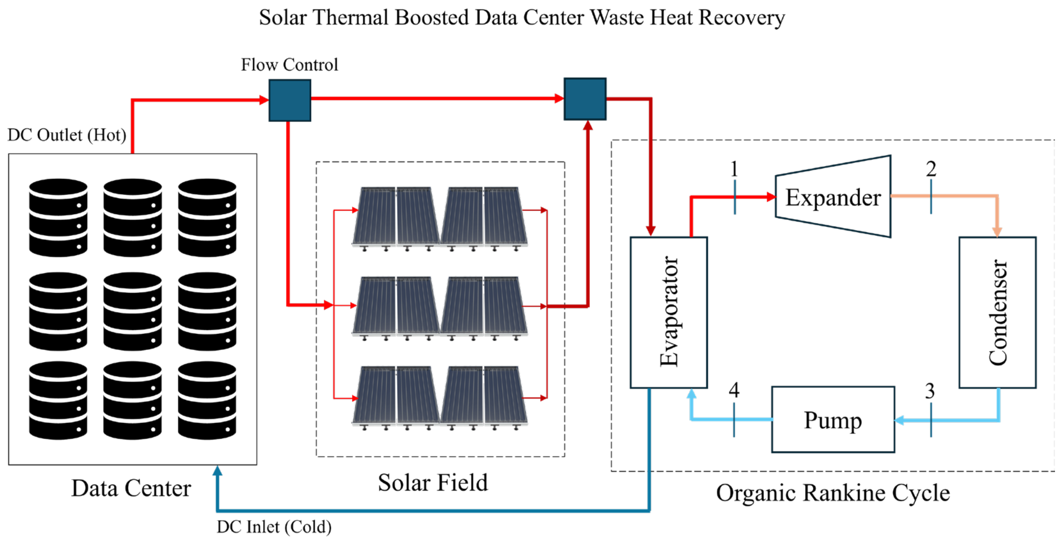
Traditional ORC-based WHR system for data centers

Solar Thermal Boosted WHR

Proposed Solution

- Temperature boost using solar thermal
- High ORC thermal efficiency
- Low cost – LCOE
- Increased reliability through solar integration
- Flat plate collectors (could use parabolic trough)
    - Cheapest
    - Suitable for temperatures < 100 ˚C

Method: A techno-economic assessment



Solar thermal boosted WHR system for data centers

Methodology: Organic Rankine Cycle

- Organic Rankine Cycle
  - Python-based simulation model with hourly data
  - ORC modeled with standard thermodynamic

$$P_1, h_1, s_1 = f(x_1, T_1) \tag{1}$$

$$h_{2,s} = f(s_1, P_2) \text{ and } h_2 = h_1 + \eta_t(h_{2,s} - h_1) \tag{2}$$

$$h_4 = h_3 + \frac{1}{\eta_p}(h_{4,s} - h_3) \tag{3}$$

$$\eta = \frac{W_{net}}{Q_{in}} = \frac{(h_1 - h_2) + (h_3 - h_4)}{h_1 - h_4} \tag{4}$$

Economic Factors

→

Component	Cost Correlation
Condenser	$Cost_c = 12{,}300 \times \left(\frac{\dot{Q}_c}{50}\right)^{0.76}$
Generator	$Cost_g = 1{,}850{,}000 \times \left(\frac{\dot{P}_g}{11{,}800}\right)^{0.94}$
Pump	$\log(Cost_p) = 3.3892 + 0.0536 \times \log(\dot{P}_p) + 0.1538 \times \{\log(\dot{P}_p)\}^2$
Turbine	$\log(Cost_t) = 2.2476 + 1.4965 \times \log(\dot{P}_t) - 0.1618 \times \{\log(\dot{P}_t)\}^2$
Evaporator	$\log(Cost_e) = 3.2138 + 0.2688 \times \log(\dot{Q}_e) + 0.0796 \times \{\log(\dot{Q}_{eva})\}^2$
Solar Field	$Cost_{FPC} = C_{Solar} \times A_{Collector}$

- Flat Plate Collectors
  - Modeled using Duffie & Beckman method
  - Useful heat gain and outlet temperature depend on:
    - Irradiance
    - Heat losses
    - Ambient conditions

$$Q_u = \dot{m}C_p\,(T_{f,out} - T_{f,in}) \tag{5}$$

$$\eta_c = \frac{Q_u}{A_c\, I_T} \tag{6}$$

$$Q_u = A_c F_R\,[S - U_L(T_{f,in} - T_a)] \tag{7}$$

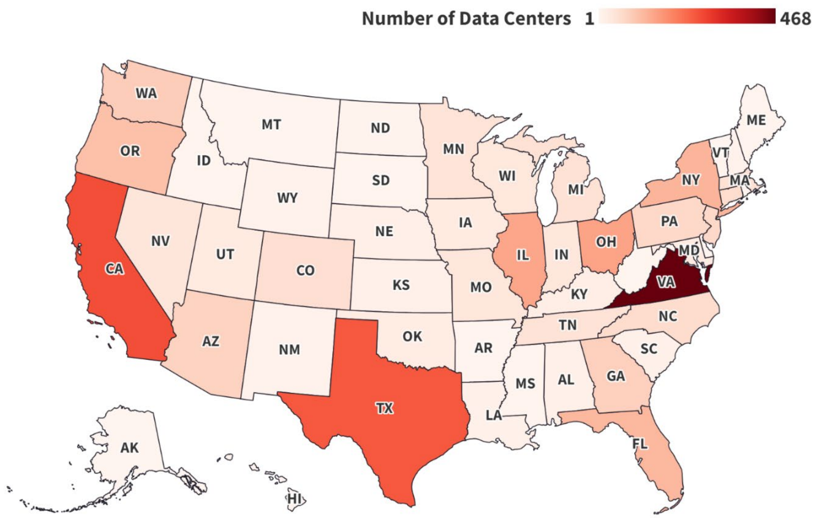
Parameter	Value
Absorptivity	0.95
Transmissivity	0.2
Total mass flow rate	0.3 (kg/s)
FPC area	0.375 (m^2)
FPC tilt	Latitude
Fluid	Water

Case Study

- Location: Ashburn, VA
- Simulation Period: One day in each season

Data Center Waste Heat Specifications

- Cooling type: Liquid cooling
  - Constant heat output
  - Waste heat supply temperature 50°C
  - Cold supply to data center 25°C



Number of data centers in each US state

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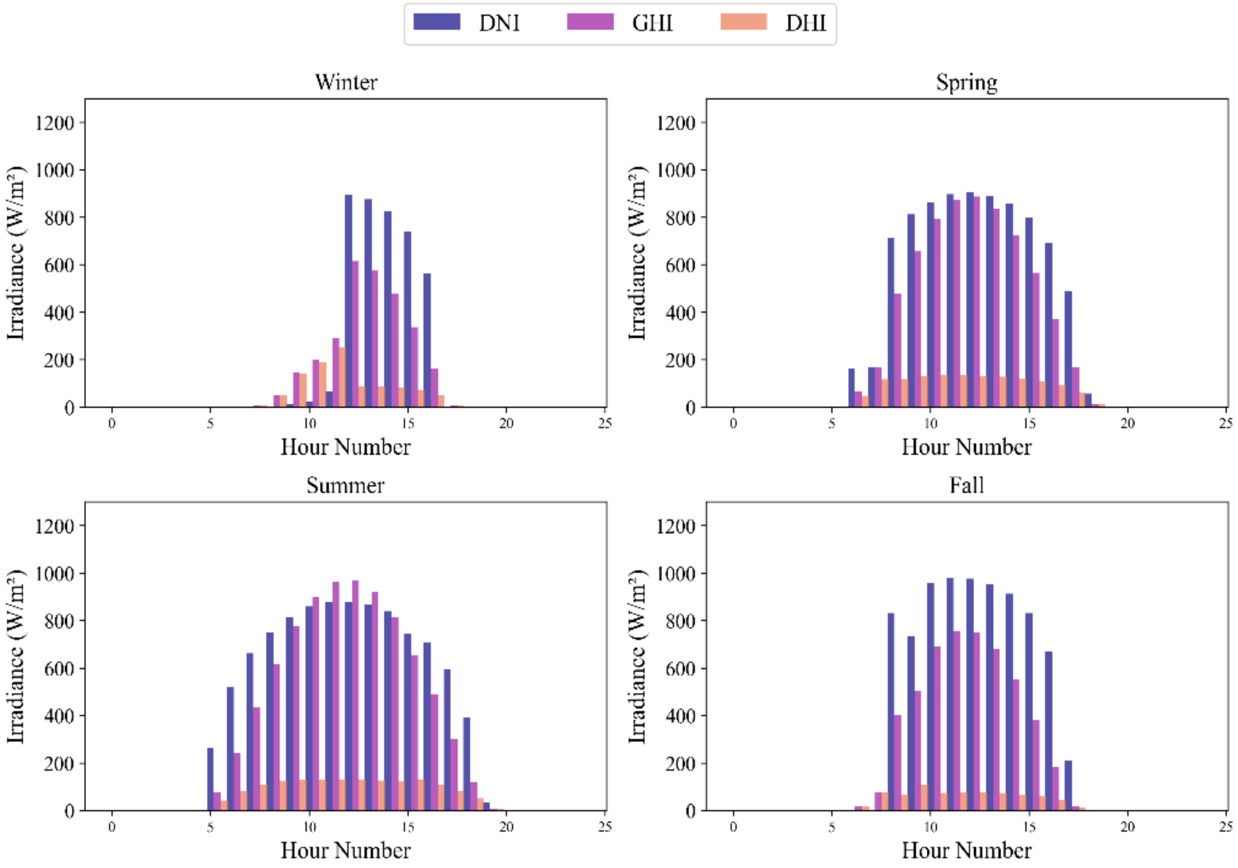
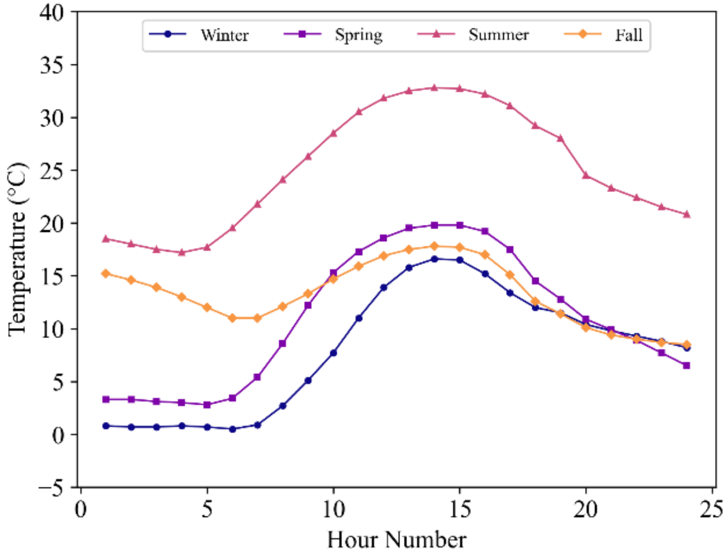
Case Study (Seasonal Variation)



Solar resource in Ashburn, VA



Ambient temperature in Ashburn, VA

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Results: Thermal Efficiency Enhancement

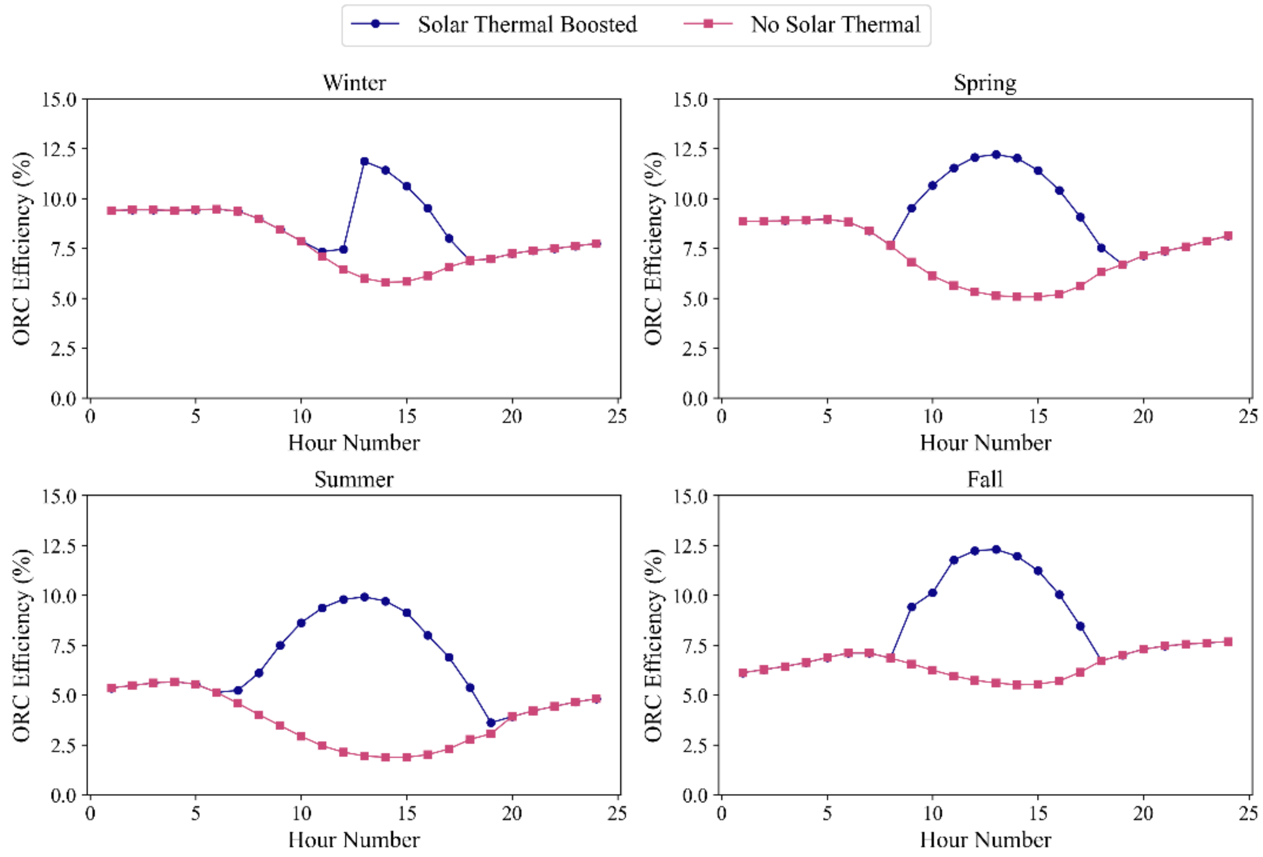
Key Findings

- Up to 8% increase in efficiency during peak solar hours
- Solar helps offset ambient temperature degradation

Solar Boosting = Better Economics

- Power output nearly doubled (189.8 → 374.5 kWh)
- 19.09% reduction in investment per kWh
- Solar adds $20,250 but justifies cost with gains
- Solar field needs only 67.5 m^2 (rooftop ins

$$Cost\ Reduction\ (\%) = \left[1 - \frac{\frac{CapEx_{Solar}}{Generation_{Solar}}}{\frac{CapEx_{Non-Solar}}{Generation_{Non-Solar}}}\right] \times 100$$



ORC thermal efficiency comparison

Conclusions

- Multiple goals can be met:
  - Standalone power generation or heat production
  - Better utilization of empty land/space
  - Increased resiliency at economically-competitive levels
  - Boost low-temperature cycle efficiency, flexible operation
- Many questions still to be answered:
  - Largest one – how do CapEx and OpEx ***<u>scale</u>*** and what are the limits of that scaling?
  - Are these viable opportunities for manufacturers and practitioners?
  - How do we increase the concentrating solar workforce to take advantage of this moment?

Thank you!

Link to Surveys Focused on Boosting the Concentrating Solar Workforce

Current College Students

Recent Graduates

RICE UNIVERSITY
School of Engineering

HelioCon
Heliostat Consortium for
Concentrating Solar-Thermal Power