High Operating Temperature Transfer & Storage (HOTTS) System for Light Metal Production

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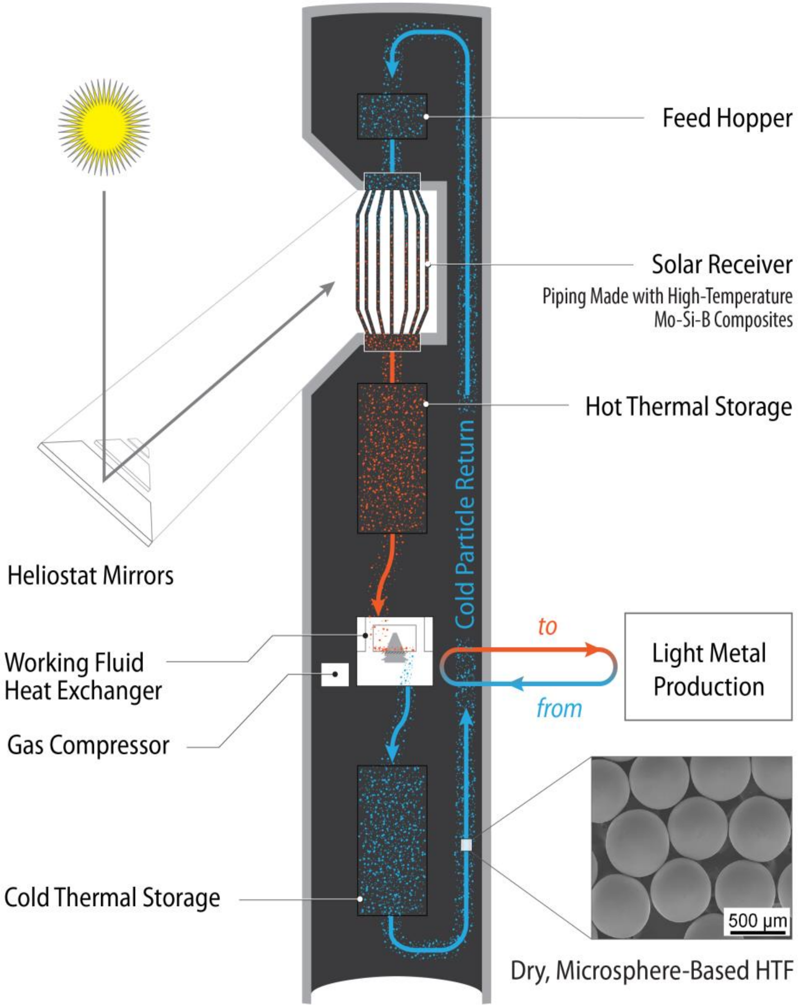


High Operating Temperature Transfer & Storage (HOTTS) System for Light Metal Production

Global Non-Profit Institute with the mission to improve the human condition by turning knowledge into practice, recognized for solving critical social and scientific problems

material dynamics & devices — High Temperature Coatings (MOC)

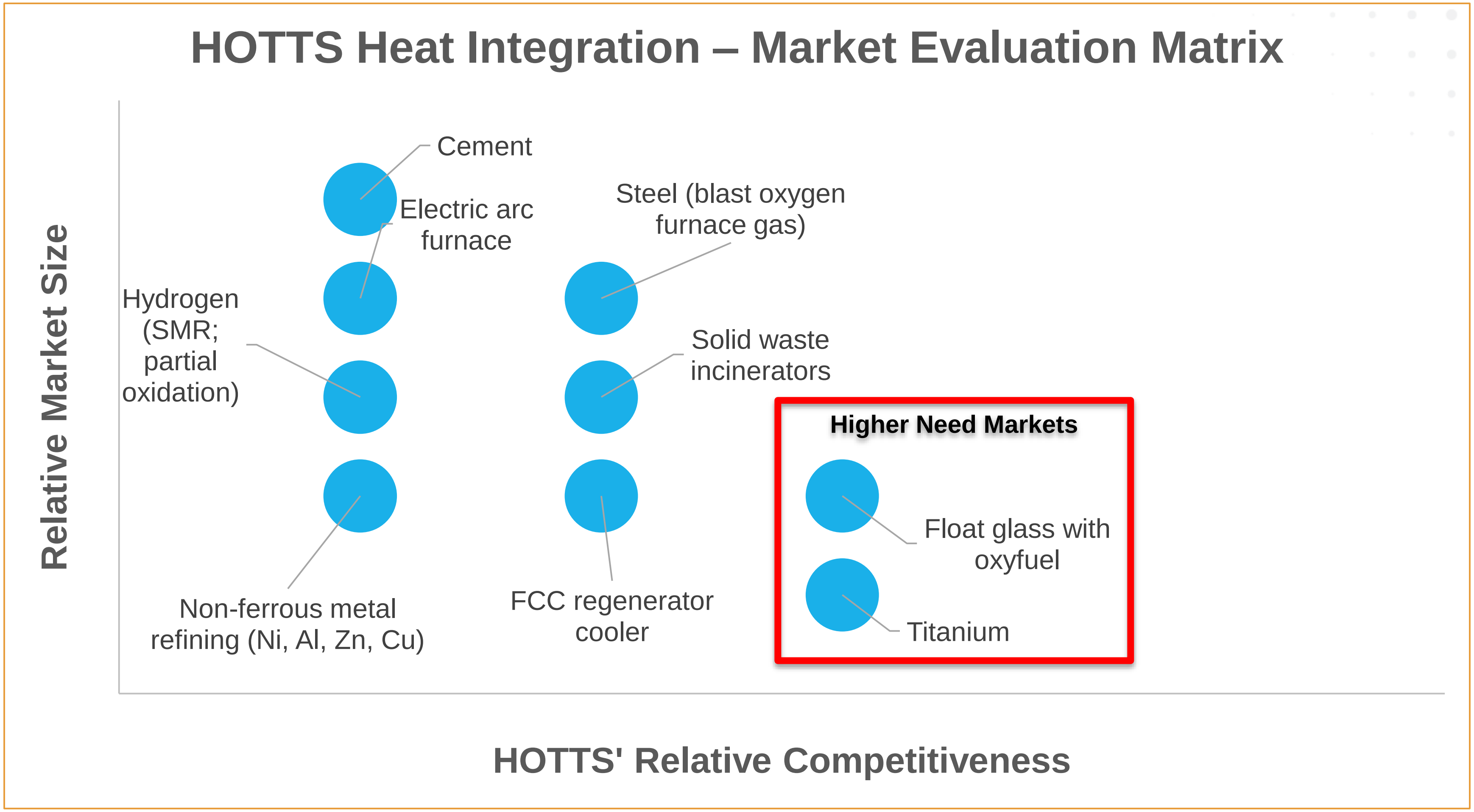
NC STATE UNIVERSITY — Fundamentals of Heat Transfer

Enable the use of renewable energy generated thermal energy in light metal production processes and Concentrated Solar Power with early market demonstration for heat recovery in industrial applications

Project Summary

- Technical milestones and deliverables have been met to date, but economics are challenging
- Renewable energy heat production from solar thermal integrated into a light metals plant is >5 times the cost relative to burning natural gas
- For heat integration, amount of available heat in world-class Titanium plant not enough to justify capital; float glass plants are most amenable
- Longer term implementation into the CSP market (5-10 years) can reduce the power price by 15-20%; overall cost comparison with PV + energy storage to be evaluated

Market Selection for Heat Integration



Heat Recovery Costs for Float Glass

	HOTTS Heat Integration – U.S. (10 MW_t)	HOTTS Heat Integration – Japan (10 MW_t)
Levelized Cost Of Heat for HOTTS ($/kWh)	$0.044[a]	$0.059[a]
Natural Gas (with Oxyfuel) Combustion Cost ($/kWh)	$0.021	$0.056

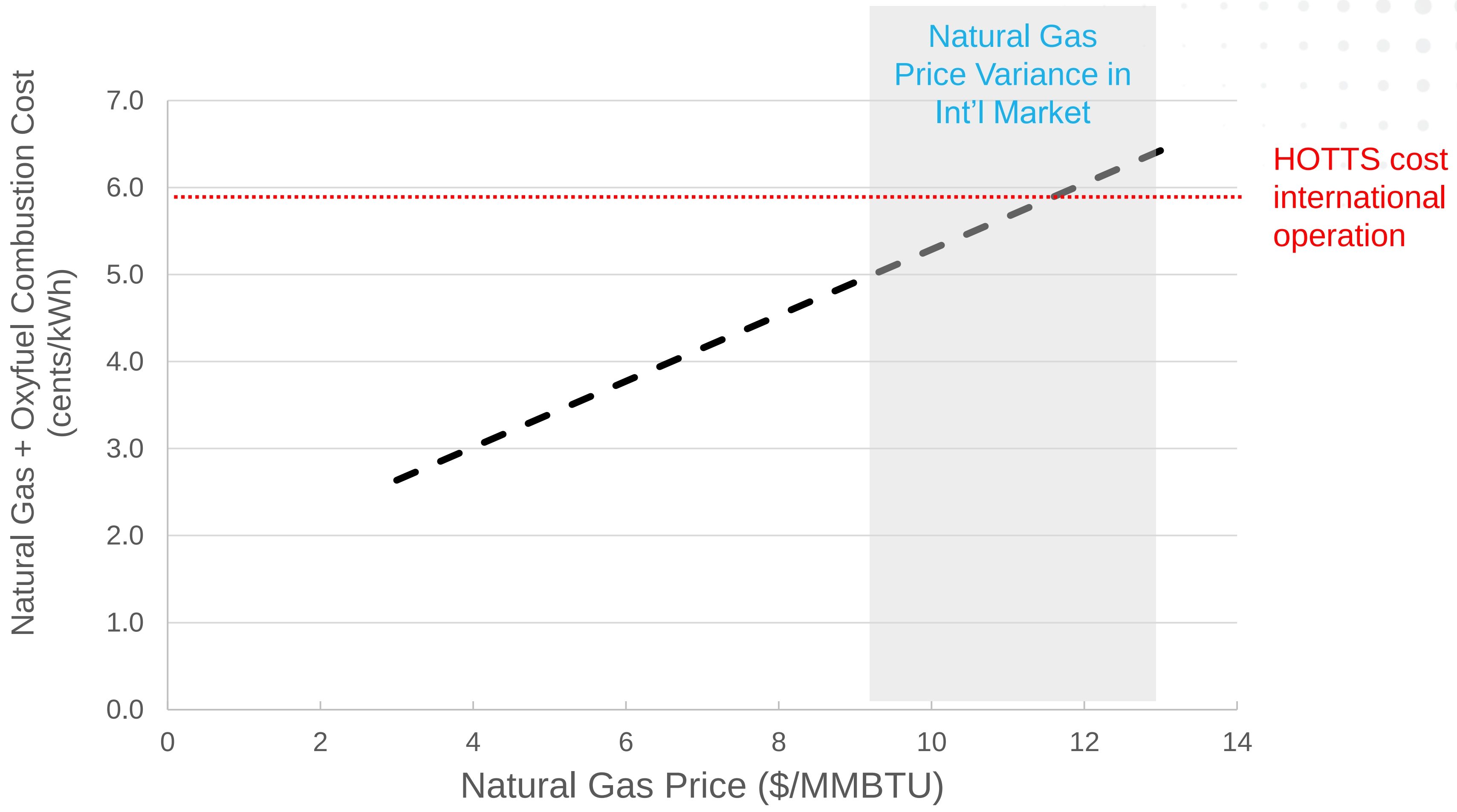
Cost estimates include the effects of US vs Japanese labor rates (1.25x US) and electricity rates (2x US)

- Cost of incumbent (natural gas combustion) sets baseline:
  - $0.013/kWh for US, $0.041/kWh for Japan ($4/MMBTU and $11/MMBTU)
- Marginal cost of O_2 is 0.75 to 1.5 cents/kWh[b]
  - 0.75 cents/kWh for US, 1.5 cents/kWh international
- Carbon hurdle rate (CO_2 avoidance) in US is about $150/t CO_2 (~$0.024 extra per kWh)

HOTTS technology competitive in international markets (initial entry point)

(a) Assumes 17 year lifetime, 7.9% real discount rate
(b) Assumes 0.025 to 0.05 $/kg O_2 (0.1 to 0.2 $/100 scf)

Competitiveness for Float Glass

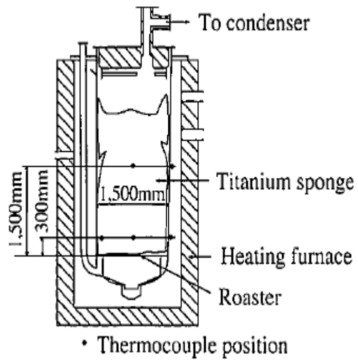


International Monetary Fund, 2021 Natural Gas Projection

Titanium waste heat recovery

Application Description

- Vacuum distillation process
- Stainless steel vessel
- 1040°C
- 3-4 days



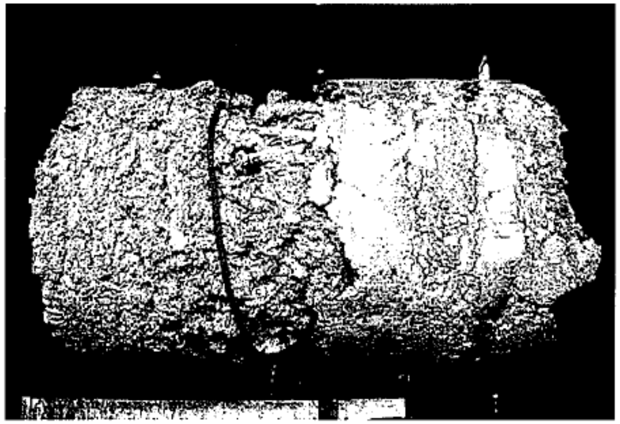


Photo 2 Titanium sponge mass with diameter of about 1.7 m and height of about 2.5 m (shown as placed on side)

Ability to compete:

Current approach is air cooling (which takes 3-4 days) with no heat recovery.

Market Size in 2020 14-28 MW_t

- Current global capacity: 330,000 t / year
- Expected growth: 5% / year
- Average plant size: 14,500 t / year
- New plants per year in 2020: 1-2 (global)
- Total market size: 14-28 MW_t

- *Waste heat for Ti sponge limited by conductivity through diameter*
- *Amount of heat available is almost a factor of 20x less than a float glass plant!*
- *Technology will not scale down cost effectively*

Technical Concept

- Use particle HTFs that raise the upper operating temperature of solar thermal from 600 to >1100°C and are not limited by freezing
- Develop the ability to store high-quality, thermal energy with process integration capabilities for continuous operation
- Develop composite or coated metals that can withstand high temperatures and resist erosion

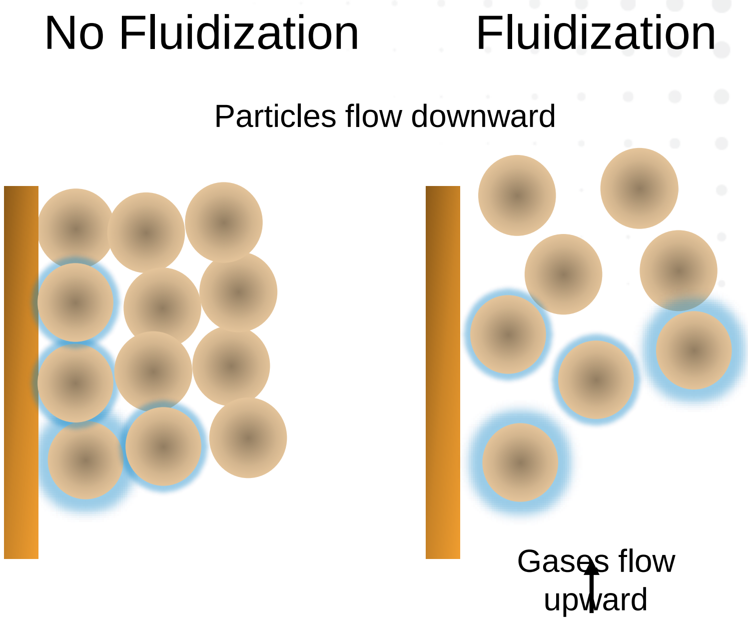


Table 1. HTFs and Their Primary Limitations	
Heat-Transfer Fluid[10]	Major Limitations
Solar salt (commercial CSP plants)	Decomposes at T>650°C; solidifies below 228°C
Molten metals	Highly corrosive toward walls of CSP pipes, storage tanks; prone to oxidation
High-pressure gas (e.g., air, S-CO_2)	Requires high-pressure piping and pump; lacks long-term thermal storage
Molten glass	Typically solidified below 400–600°C; prone to oxidation
Falling curtain pHTF	Low particle volume fraction (<0.1[3]), limited heat transfer between particles; sintering of particles during overnight storage[5]

Technical Progress to Date

Research program is advancing two high-temperature technologies:

Particle Heat Transfer Fluid

- Demonstrated particle compositions that resist sintering up to 1,300ºC/16 h
- Achieved effective heat transfer coefficient > 600 W/m^2-K
- Developed pilot-scale heat transfer unit for operating temperatures above 600ºC

Mo-Si-B Material of Construction

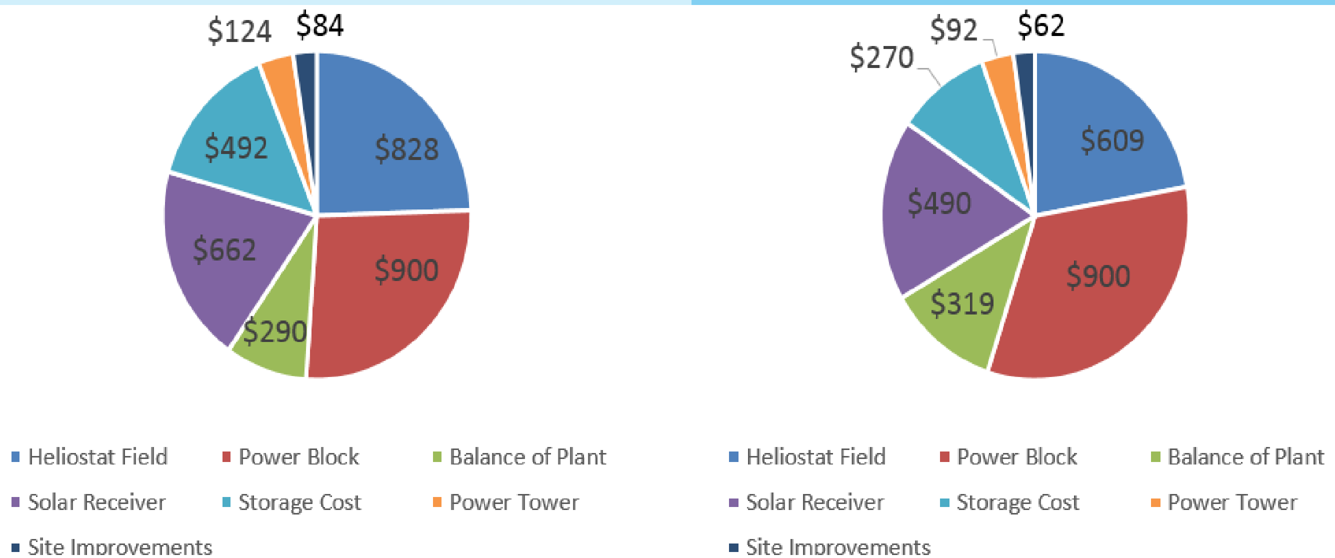
- Demonstrated oxidative resistance of hot-pressed coupons up to 1,650ºC in air
- Developed two approaches for depositing protective coatings
- Thermal Spray approach chosen to coat tubes for commercial scalability

- All milestones and deliverables have been achieved per plan
- The measured effective heat transfer coefficient of technology has already exceeded project commitments, with many ideas still to investigate (expect to approach 1000 W/m^2-k)
- Coating of tube (inside / outside) with zero defects by thermal spray is last high-risk milestone to achieve by 30 September

TEA Highlights: CSP Case

(Costs in $/kW$_e$)

Current Plant (Molten salt + Rankine cycle)	Proposed Plant (pHTF + sCO2 cycle)



HOTTS LCOE reduction due to lower capital costs (per kWe) in

1. Heliostat Field
2. Solar Receiver
3. Storage Costs

Size = 265 MW$_t$	Molten Salt Plant Cost	pHTF Plant Cost
Total Installed Capital Costs contingency 20%	$405M	$444M
$/Installed kWe	$4050	$3300
CSP Levelized Cost of Electricity	$0.26/kWh	$0.22/kWh

CHANGING WHAT'S POSSIBLE

Demo Requirements

- For the CSP application, the next phase requires testing of a solar receiver with pHTF and high temperature coatings integrated with a high-pressure S-CO_2 power cycle in simulated, real-life conditions
  - Size of solar receiver equivalent to 0.5 MW_{th}
  - $5 – 10MM
  - Partners include those with testing facilities in place, power cycle integrators and a leading equipment supplier into CSP industry
  - Position technology to be demonstrated at 10-50MW+ scale
- For heat recovery in the float glass industry, the next phase requires demonstration of technology in a float glass facility on a slip-stream
  - Size of slip-stream to ensure each component is at commercial scale
  - $3 – 5MM
  - Successful demonstration leads to technology commercialization for industry, including both retrofits of existing plants and new-builds

Future Goals/Closing Thoughts

- To close out this project successfully, we need to:
  - Demonstrate complete coating and survivability of a tube with recession rate of less than 0.05 μm/hr at 1300°C in air due to oxidative effects for 100 hours
  - Demonstrate a heat transfer coefficient that approaches 1000 W/m^2-K
  - Create interest from future funders for CSP and/or heat integration in float glass industry
- Adoption of RTI's pHTF technology as a replacement for molten salts in CSP plants could make CSP more competitive with PV when the full cost of energy storage required for grid stability is accounted for
- With low natural gas prices for the foreseeable future, early market adoption for industrial heat recovery does not make sense for the metals industry; opportunities in the float glass industry exist in some geographies

QUESTIONS?