Industrial High Temperature Heat Pumps – Ongoing Research in the USA

Ammi Amarnath

Principal Technical Executive, EPRI

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Agenda

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Vision

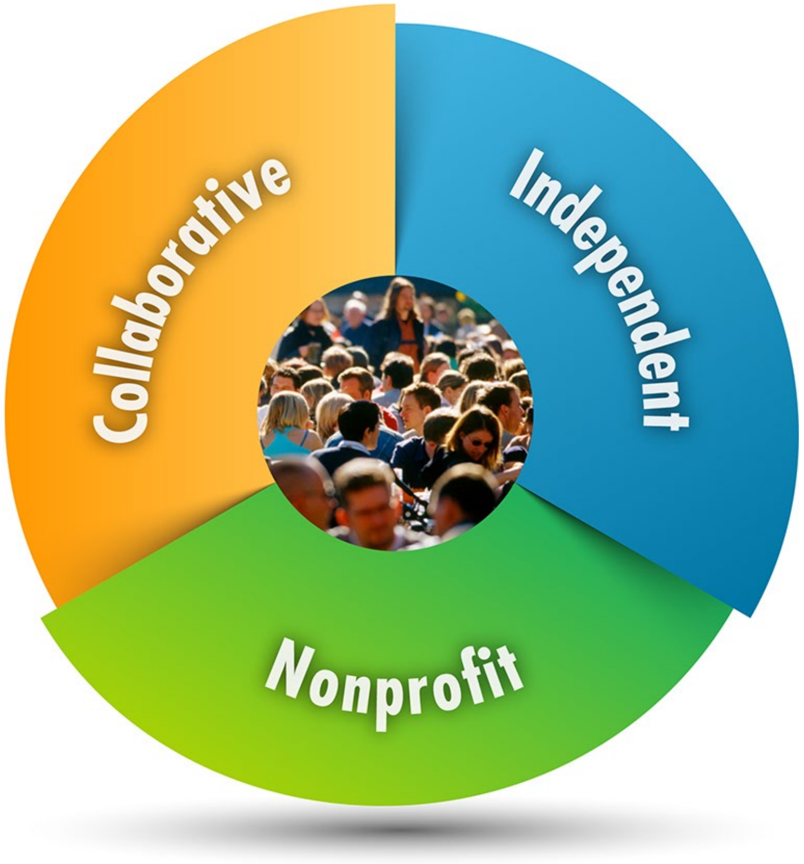
To be a world leader in advancing science and technology solutions for a clean energy future

Mission

Advancing safe, reliable, affordable, and clean energy for society through global collaboration, science and technology innovation, and applied research.

Together…Shaping the Future of Energy®

Three Key Aspects of EPRI



Collaborative

Bring together scientists, engineers, academic researchers, and industry experts

Independent

Objective, scientifically based results address reliability, efficiency, affordability, health, safety, and the environment

Nonprofit

Chartered to serve the public benefit

EPRI Accelerates Technology Advancement

LABORATORIES AND UNIVERSITIES

Basic research and development

SUPPLIERS AND VENDORS

Technology commercialization

EPRI

Collaborative technology development, integration, and application

Thought leadership illuminates emerging developments, opportunities, and trends.

Technology Innovation Scouting searches globally for emerging technologies and concepts to provide insights on industry challenges and solutions.

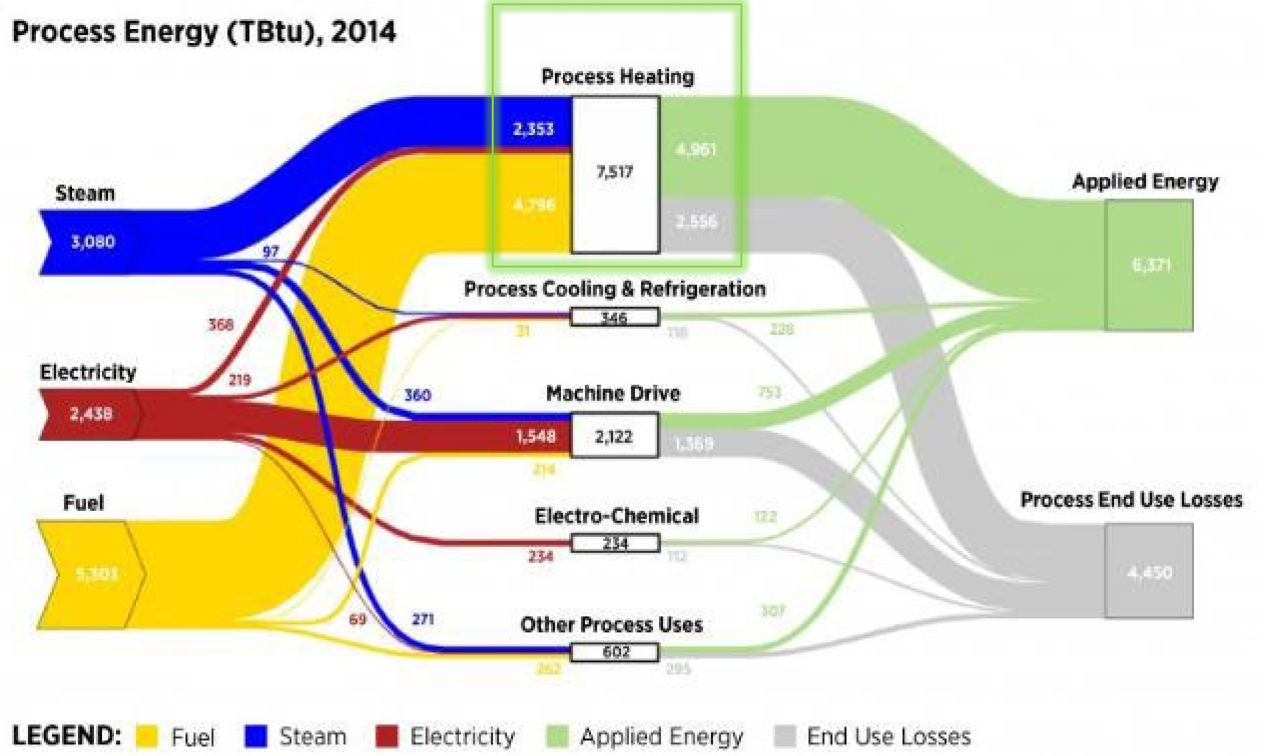
Sector R&D conducts research and demonstrations to address challenges, deploy results, and provide supporting services for existing and emerging technologies.

EPRI stimulates innovation and plays a key role in validating technology across multiple utilities, fostering widespread acceptance, and helping accelerate technology to commercial development and industry adoption

Industrial Decarbonization – Problem Statement:

Industrial Process Heating Uses Most Fossil Energy

- Total process heat (PH) energy use for U.S. manufacturing sector is 7,517 TBtu
  - Accounts for ~70% of the total process energy consumed in the manufacturing sector.
- Direct fossil fuel use for process heating is 4,796 TBtu/yr
- Direct and indirect (e.g., fuel used to generate steam) energy use for PH is 7,149 TBtu/yr
  - ~95% of all the process heating energy demand.
- About 35% of fossil energy is lost as waste heat



Source: https://www.energy.gov/eere/amo/static-sankey-diagram-process-energy-us-manufacturing-sector-2014-mecs

Problem Statement: How to use low temperature industrial waste heat?

- Low-temperature waste heat streams available abundantly in industries
- Typical waste heat are at temperatures in the 70-80 ^{o}C range
- Sources of waste heat: chillers, cooling processes, return steam condensate
- Many industries needs low-pressure steam in 120-125 ^{o}C range
- Industry applications: food manufacturing (e.g. bakeries, dairy etc.), paper, chemical, and textiles

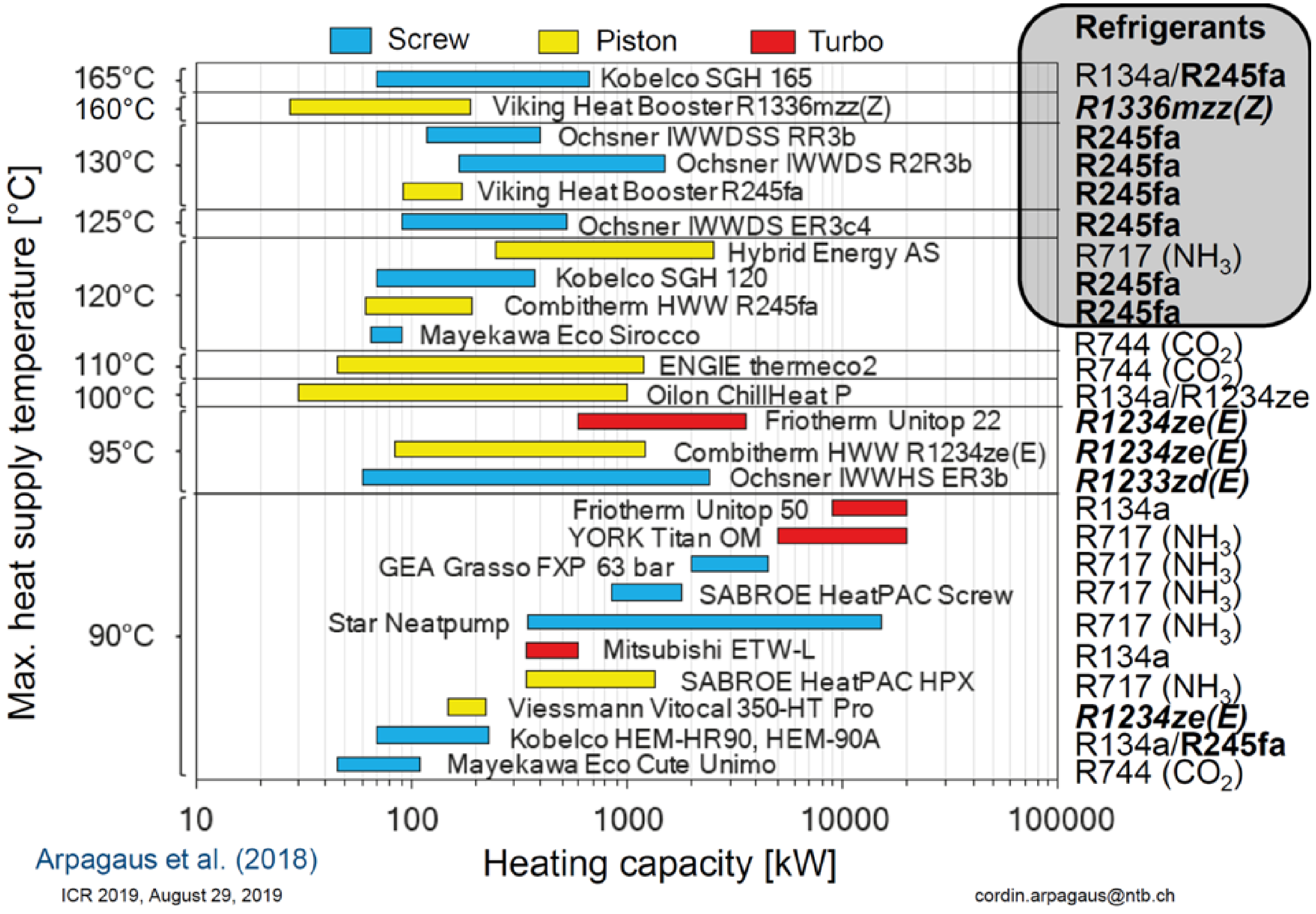
Solution: High temperature heat pump (HTHP) that can produce steam at low pressure

- Key characteristics of the heat pump:
  - Low ODP, GWP refrigerant
  - Currently no high temperature heat pump that produces steam is available in US market
  - heat pumps offer an ideal solution for industrial decarbonization in California
  - New system produce steam at 120 ^{o}C from waste heat (80 ^{o}C) @ COP* of 3.4

Photo – Courtesy AIT

*COP = Coefficient of Performance, which is a measure of system efficiency

HTHPs in Development and Refrigerants Used



Project Overview - EPRI's CEC Funded Project Objectives, Goals & Benefits

Primary Objectives

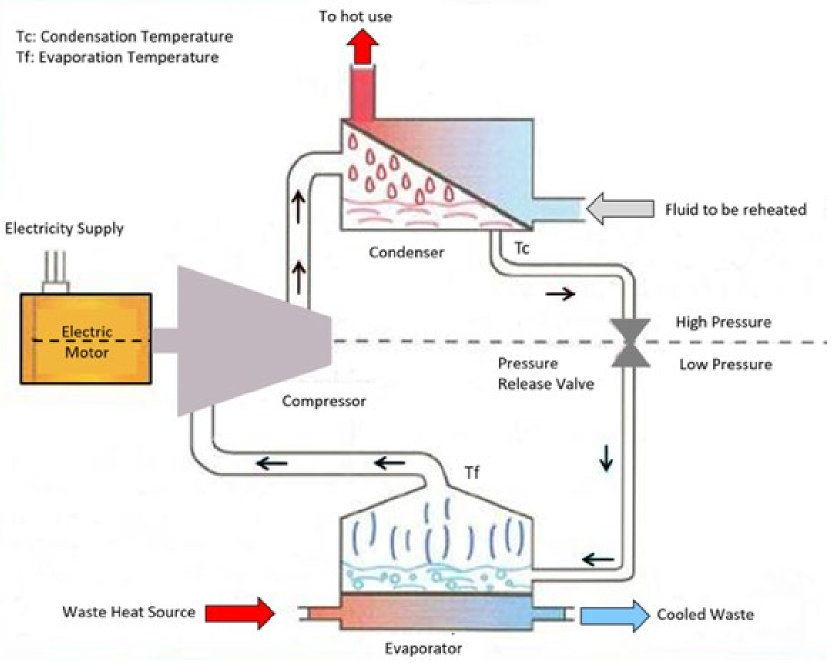
- Develop and test an advanced high temperature heat pump (HTHP) for efficient recovery of industrial waste heat
- Produce low pressure steam.

Goals

- Develop HTHP that uses near zero GWP refrigerant
- Recover waste heat at 80^0C; provide lift of 40^0C
- COP >3.4
- Move technology from TRL 3 to TRL 6.

California Ratepayer Benefits

- Decarbonization solutions to California Industries
- Potential savings of 1.3 million metric tons CO_2/ year
- Potential energy savings of 280 million therms/year



Link to CEC Agreement: https://www.energy.ca.gov/filebrowser/download/280

Performance Metrics

Performance Metric	Baseline Performance	Target Performance	Evaluation Method	End-of-Project Performance
Waste Heat Temperature Limits	70 - 80 ^oC	>120 ^oC	Laboratory Testing	125 ^oC
COP	0.8	3.4	Laboratory Testing	3.6
Estimated Equipment Capital and Installation Costs	$2540/unit or $85/kW	$2000/kW	Market Available Cost	$1500/kW
Estimated Operation and Maintenance Costs	$916	$215 (based on 3.4 COP)	Market Available Cost	$203 (based on 3.6 COP)
Other, specify	Size = 3bhp	Size = 30kW	Power Measurements in Lab	30kW

Refrigerant Selection

- Three refrigerants tested: R245fa, R1233zd(E), R1336mzz(Z)

Refrigerant Selection Criteria:

- Low GWP <5
- No ODP
- A1 (ASHRAE 34 Safety Classification)

GWP – Global Warming Potential; ODP – Ozone Depletion Potential; A1

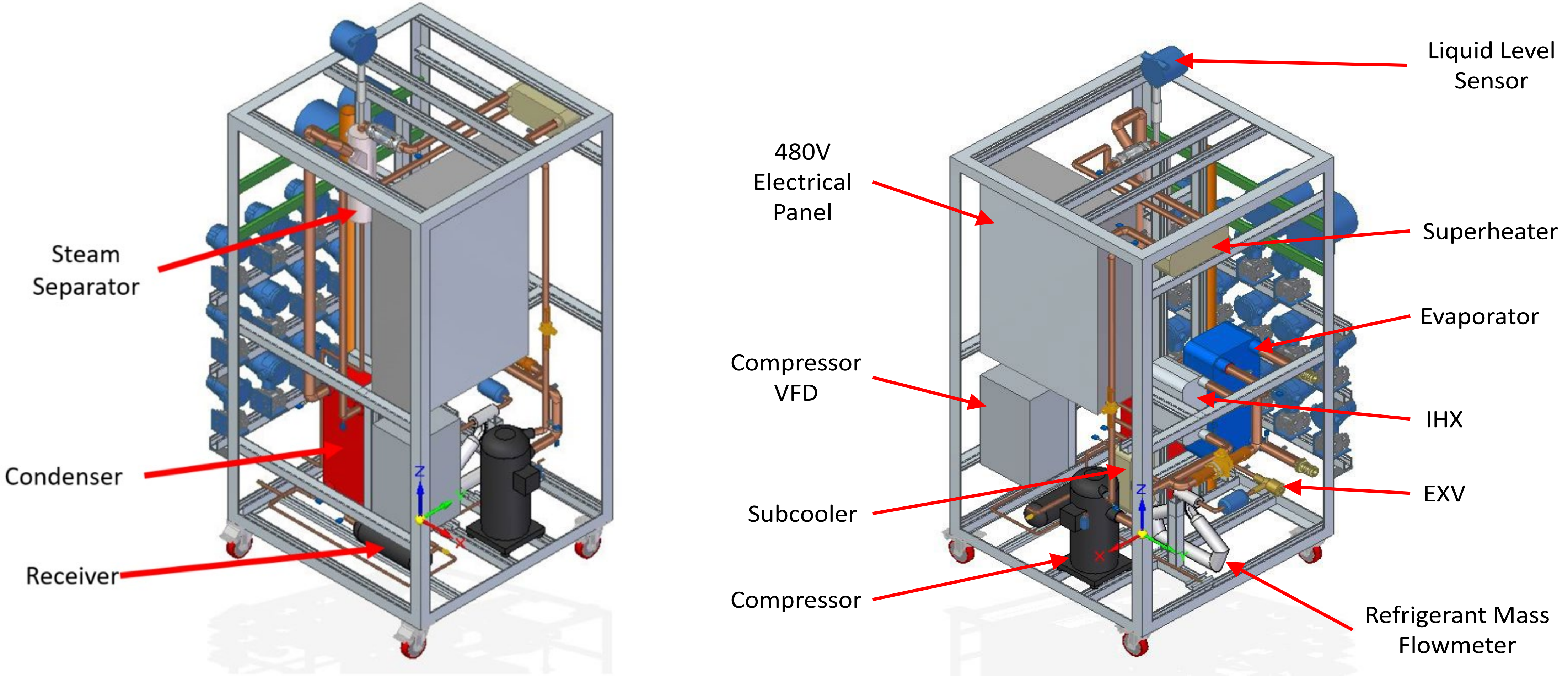
	lower toxicity	higher toxicity	
higher flammability	A3	B3	LFL ≤ 0.10 kg/m³ or heat of combustion ≥19 000kj/kg
lower flammability	A2 A2L*	B2 B2L*	LFL ≤ 0.10 kg/m³ and heat of combustion ≥19 000kj/kg
no flame propagation	A1	B1	no LFL based on modified ASTM E681-85 test
	no identified toxicity at concentrations ≤400 ppm	evidence of toxicity below 400 ppm (based on data for TLV-TWA or consistent indices)	

*A2L and B2L are lower flammability refrigerants with a maximum burning velocity of < 10 cm/s.

Refrigerants	MW [g/mol]	Tcrit [C]	Pcrti [MPa]	Vaporization Heat [kJ/kg] at 125 [C]	Saturated Vapor Density [kg/m³] at 75 [C]	ODP [-]	GWP [-]	ASHRAE Std 34 Satety Class [-]
R245fa	134.0	153.9	3.65	105.1	38.3	0	858	B1
R1233zd(E)	130.5	166.5	3.62	117.6	30.7	0.00034	1	A1
R1336mzz(Z)	164.1	171.4	2.90	107.1	24.4	0	2	A1

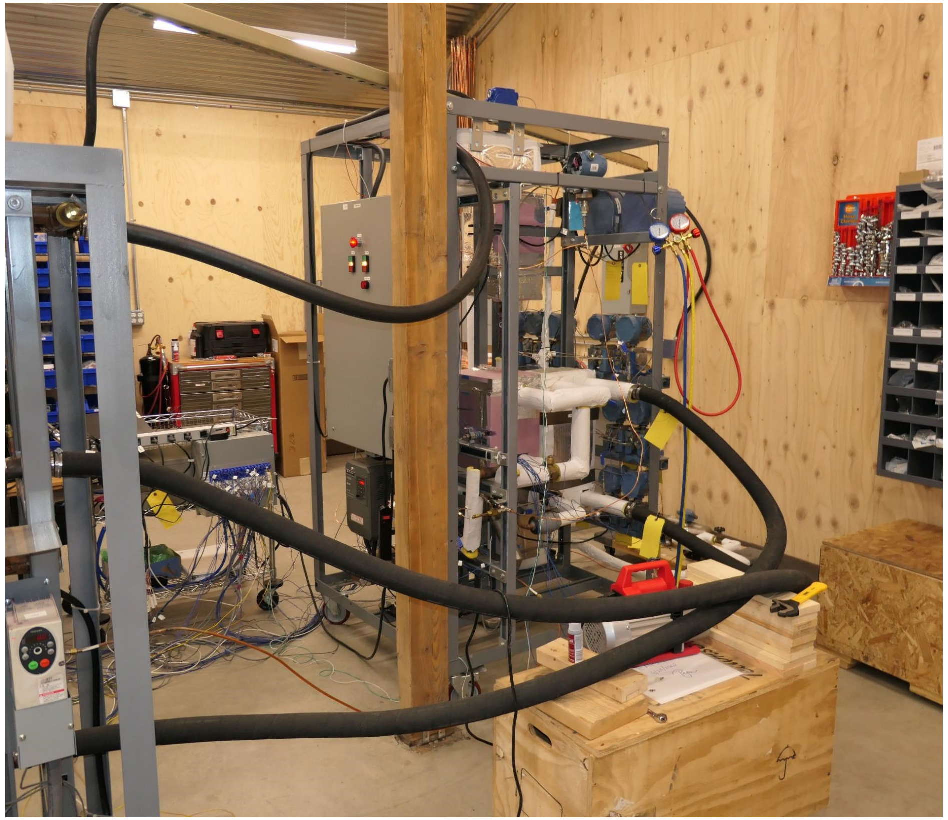
Refrigerants	q_tot [kJ/kg]	q_tot [kJ/m³]	w_th [kJ/kg]	w_elec [kJ/kg]	COP_th	COP
R245fa	128.11	4614.43	27.71	34.38	4.62	3.73
R1233zd(E)	138.83	4027.04	28.60	35.48	4.85	3.91
R1336mzz(Z)	116.92	2706.68	24.54	30.44	4.77	3.84
R245fa	1	1	1	1	1	1
R1233zd(E)	1.084	0.873	1.032	1.032	1.050	1.050
R1336mzz(Z)	0.913	0.587	0.886	0.886	1.031	1.031

Prototype System
Dimensions: 1m (l)x 1m (w) x 1.8m (h)



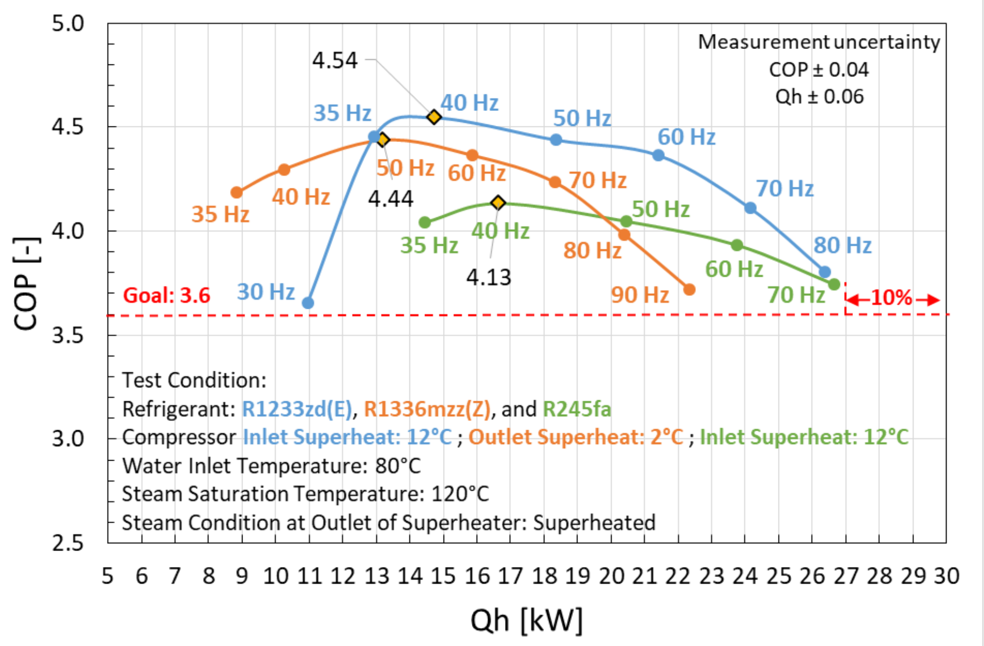
Final Design Layout

Instrumentation and Monitoring



Results of Laboratory Testing

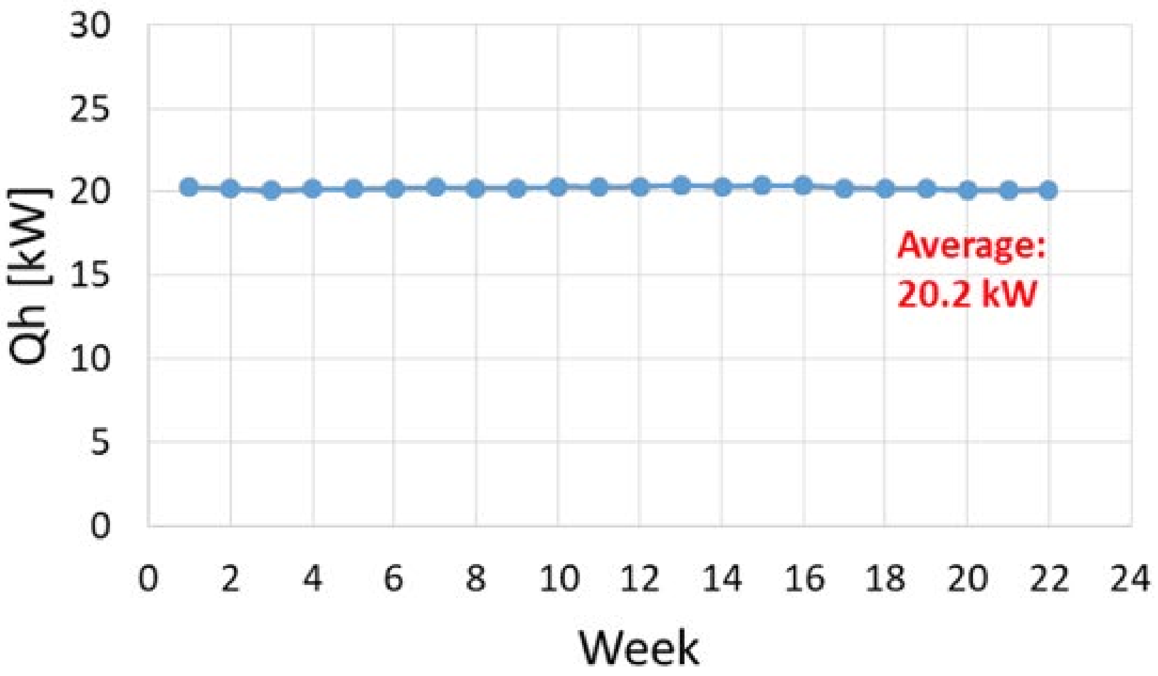
- The COP shows results above the target values of 3.4
- The heating capacity of 25 kW is achieved at compressor speeds around VFD set point of 80 Hz (=1.3 times rated compressor speed)
- Repeatability: The prototype system runs reliably and has shown that repeated test conditions produce similar results
- System has been optimized to achieve an average COP of 3.6 at an average heating capacity of 25kW (Qh) and COP of 4.0 is easily achieved at an average heating capacity of 20kW (Qh).

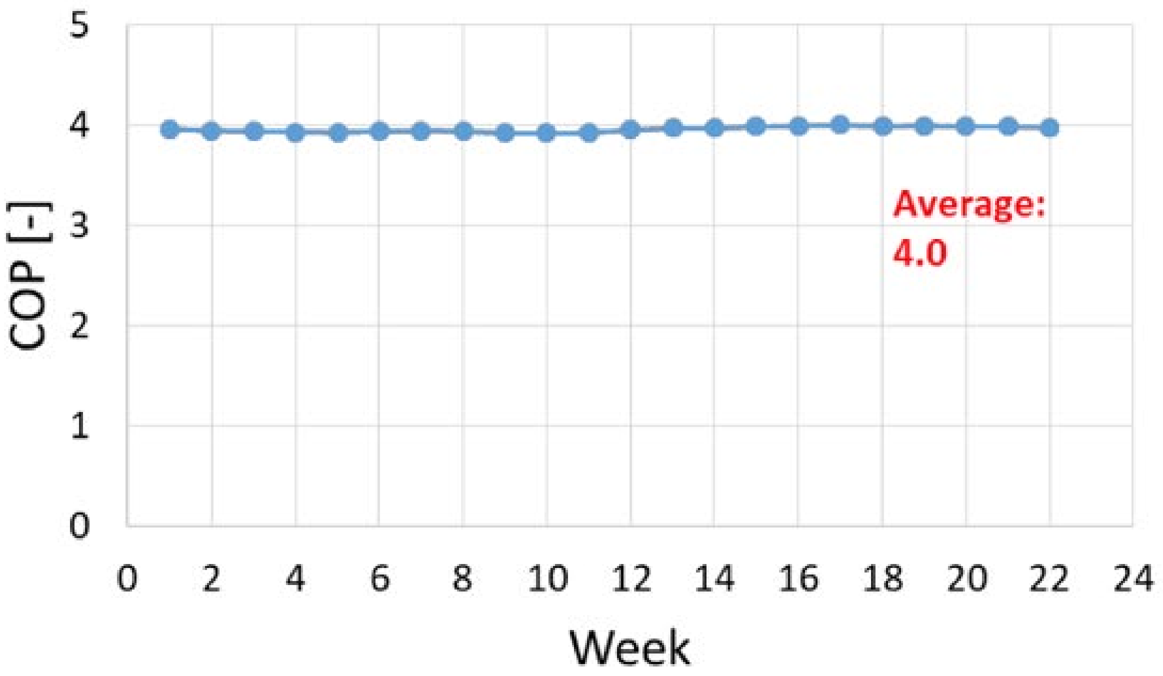


Refrigerant	VFD Set Point (Hz)	Temp Lift (oC)	Average COP (-)	Average Qh (kW)
R1233zd(E)	60	40	4.0	20
	80	40	3.6	26

The refrigerant selected for prototype testing is R1233zd(E)

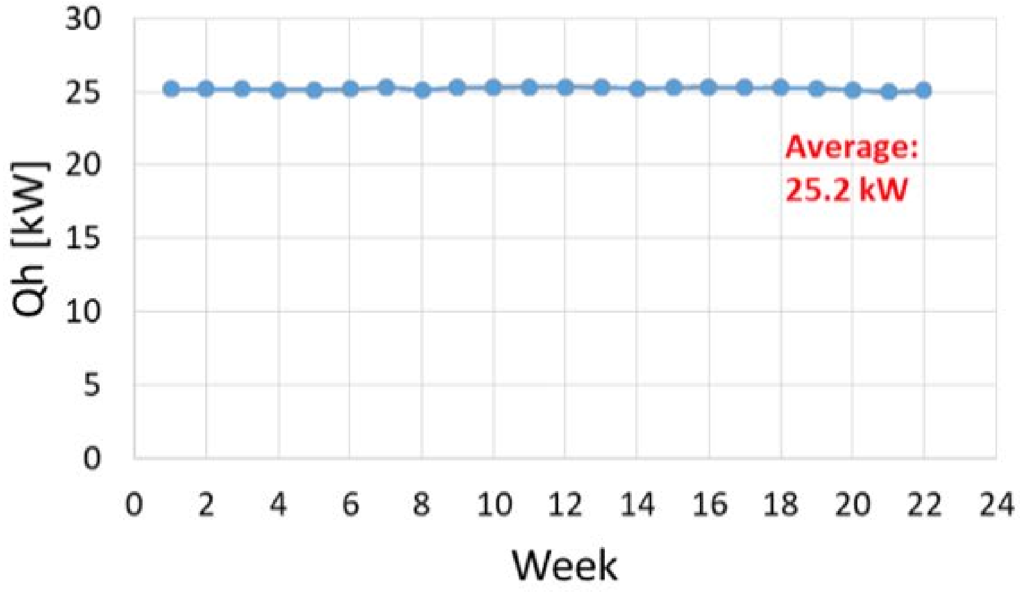
M&V for 6 Consecutive Months
Test Condition: 60Hz

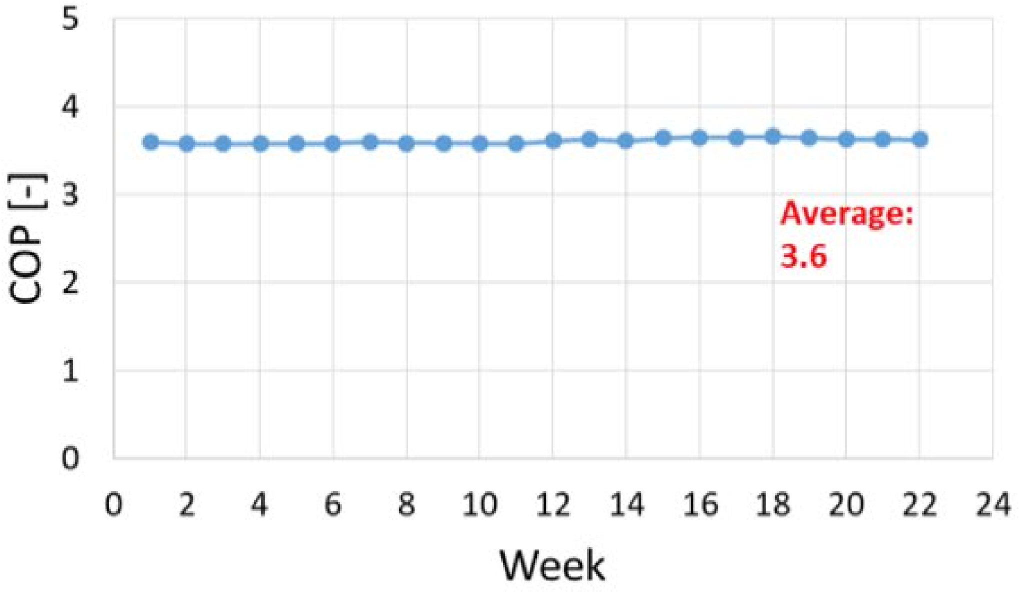




- Each data point is the average steady state value of 4 tests
- Consistent results over 24-week (6 month) period
- Average COP of 4.0 is greater than target of 3.4 and end-of-project goal of 3.6 at 60Hz
- Achieves a heating capacity of 20.2 kW

M&V for 6 Consecutive Months
Test Condition: 80Hz





- Each data point is the average steady state value of 4 tests
- Consistent results over 24-week (6 month) period
- Average COP of 3.6 is greater than target of 3.4 and equal to end-of-project goal of 3.6 at 80Hz
- Achieves the heating capacity of 25.2 kW

Next Steps

- Enhanced lab tests at EPRI Knoxville – with R1336mzz(Z) (and additional?) refrigerants
- Analysis of commercialization potential
- Field test – move toward commercialization
- Work with equipment manufacturers to build commercial system(s)
- Technology transfer – work closely with stakeholders

Summary

- Test results from the prototype are promising. Achieves targeted performance levels.
- Technology has potential to recover abundantly available waste heat
- Low pressure steam is produced - can be used readily in many processes
- Commercialization challenges exist (replace existing boilers)
- A variety of industrial applications (Food, Chemical, Pulp and Paper etc.)