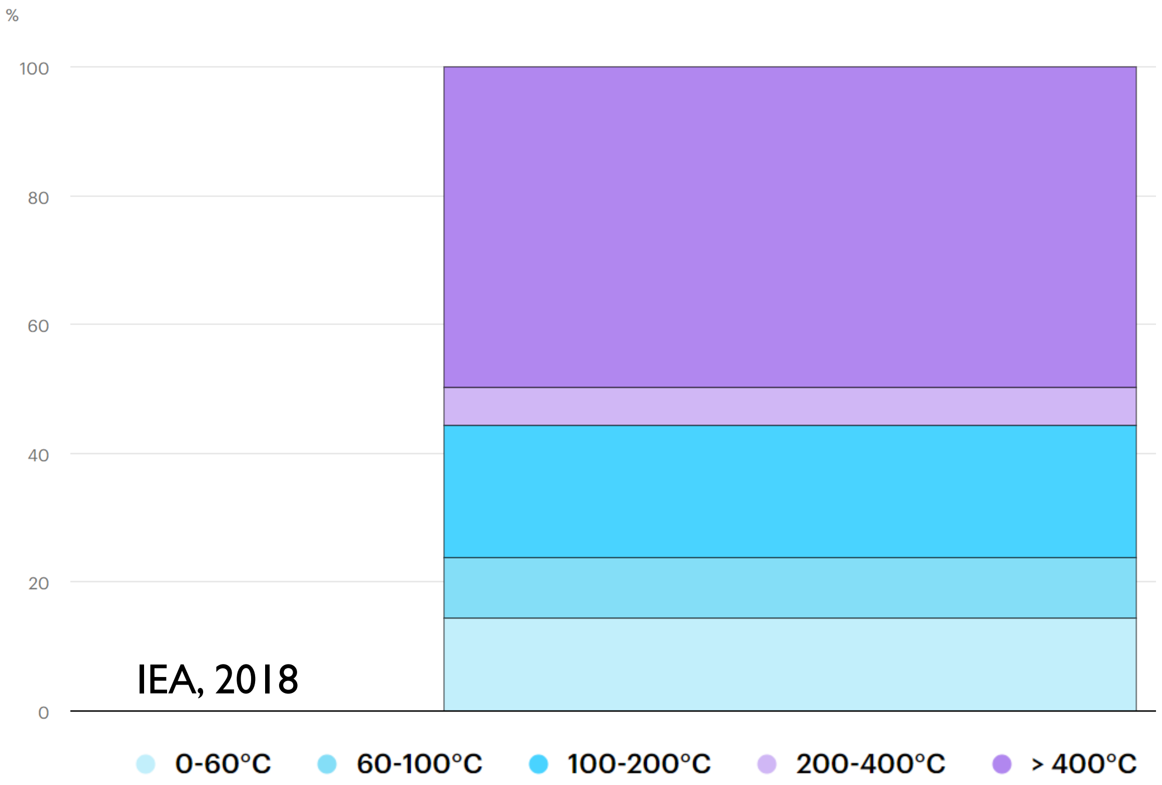
Industrial Heat Pump Technology Overview and Development Needs

SOUTHWEST RESEARCH INSTITUTE®

IPER 2024

Michael Marshall

Taking IHPs from hot water to steam



Hot Water

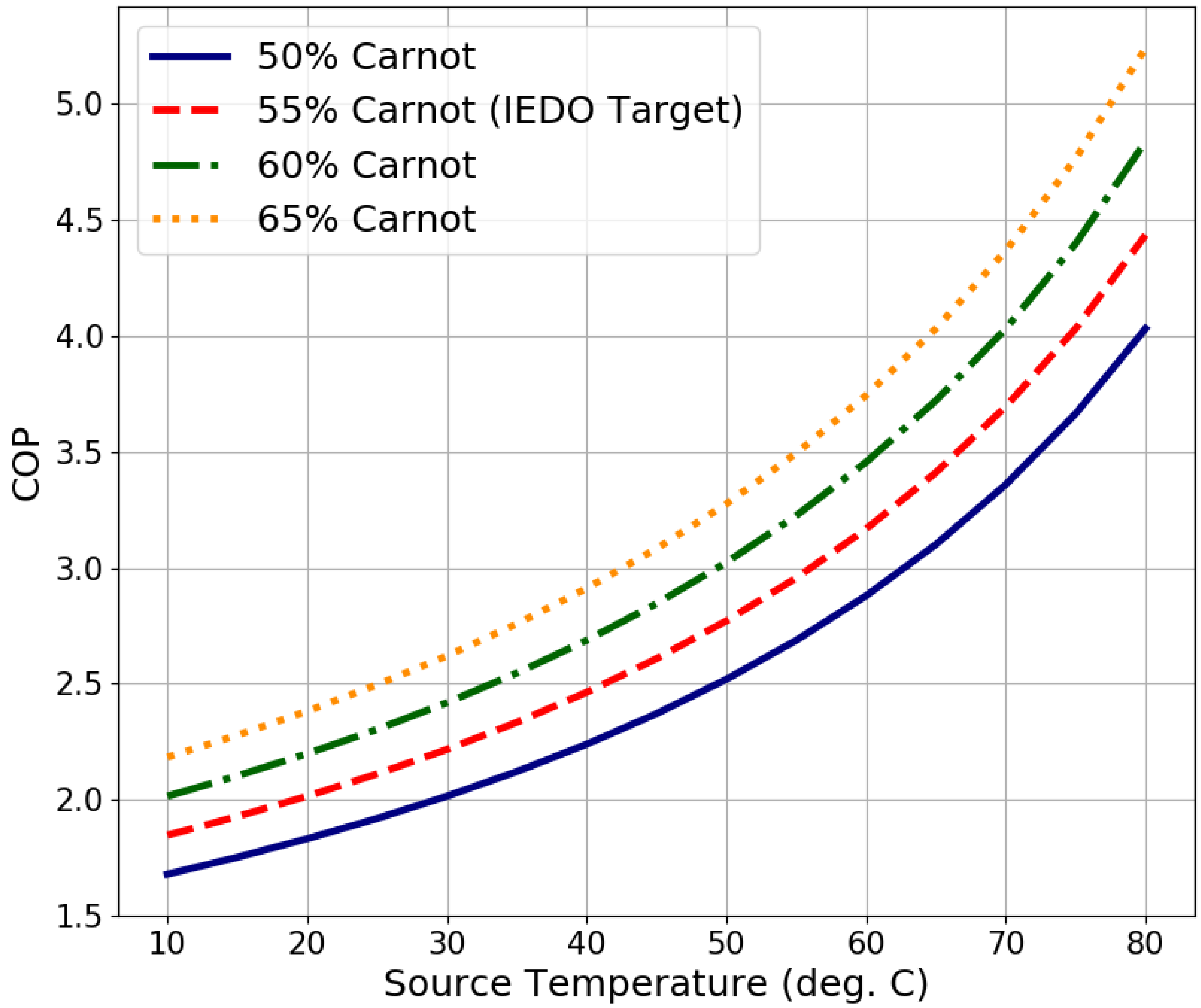
- Numerous worldwide installations of industrial heat pumps for hot water supply (<100°C).
- Simultaneous process cooling can also be achieved.

Steam

- Process heat from 100-200°C makes up 20% of all industrial process heating demand.
- Steam generation is ripe for industrial heat pump innovation, an area served by natural gas boilers currently.

Steam requires high temperature lifts, high temperature sources

- Assume a heat sink of steam at 3 bar (130°C saturation temperature).
- Typical achievable efficiencies for IHPs are 40-55% of Carnot.
- To maximize efficiency, utilize process waste heat, not ambient source.



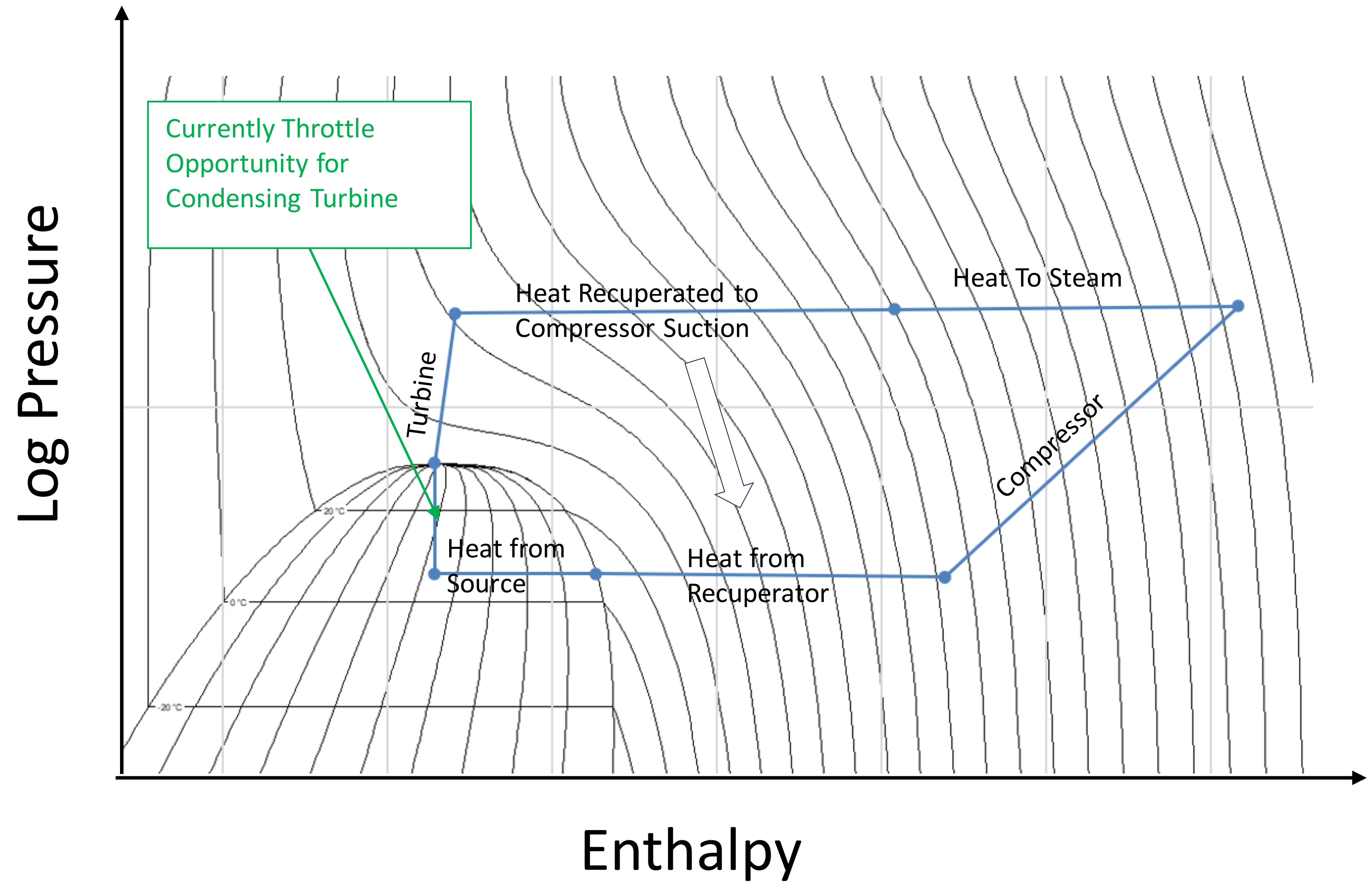
The optimal refrigerant is application specific

Refrigerant	GWP	Critical Temp. °C	Normal Boiling Point °C	Isothermal Compressibility at 40°C, Quality = 0, 1/MPa
R1233zd(E)	1	166	18	5.04
C_4H_{10} (R600)	4	152	0	2.98
R1234ze(Z)	<1	150	10	3.88
NH_3 (R717)	0	132	-33	0.78
R1234ze(E)	<1	109	-19	1.64
CO2 (R744)	1	31	-79	

- The higher the critical temperature of the refrigerant, the higher steam pressure that can be produced with a competitive COP.
- Numerous considerations exist include flammability, toxicity, local regulations, and material compatibility.

CO_2 Heat Pumps

Typical CO_2 Heat Pump Cycle



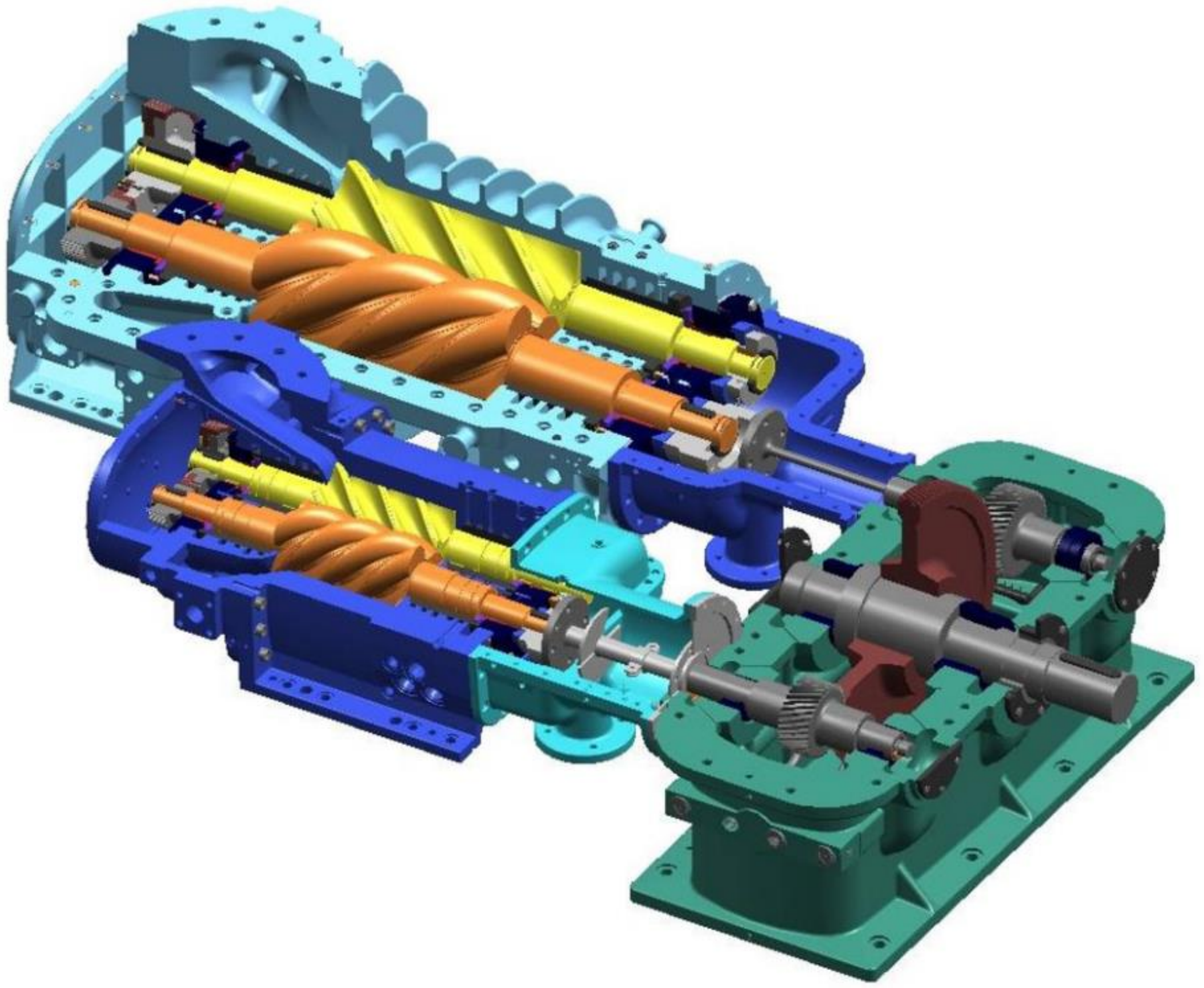
- Recuperated transcritical CO_2 cycles provide an efficient alternative to vapor compression cycles
- 60 MW CO_2 heat pump installed by MAN at Esbjerg to replace fossil boiler for district heating
- CO2 heat pumps are also being developed for ETES
- Currently use isenthalpic throttle to avoid liquid in turbine – potential to develop multiphase expander for performance improvement

MAN Heat Pump Unit

SwRI®

Centrifugal and screw compressors are viable options

- Key to performance of a high lift, vapor-compression cycle is a multi-stage compressor with economizer flow injected at intermediate pressure.
- Screw compressors can excel for high temperature lift requirements with two-stage units having gone up to 9 MW drivers.
- Centrifugal compressors present higher achievable isentropic efficiency and can be used for the highest capacity applications.

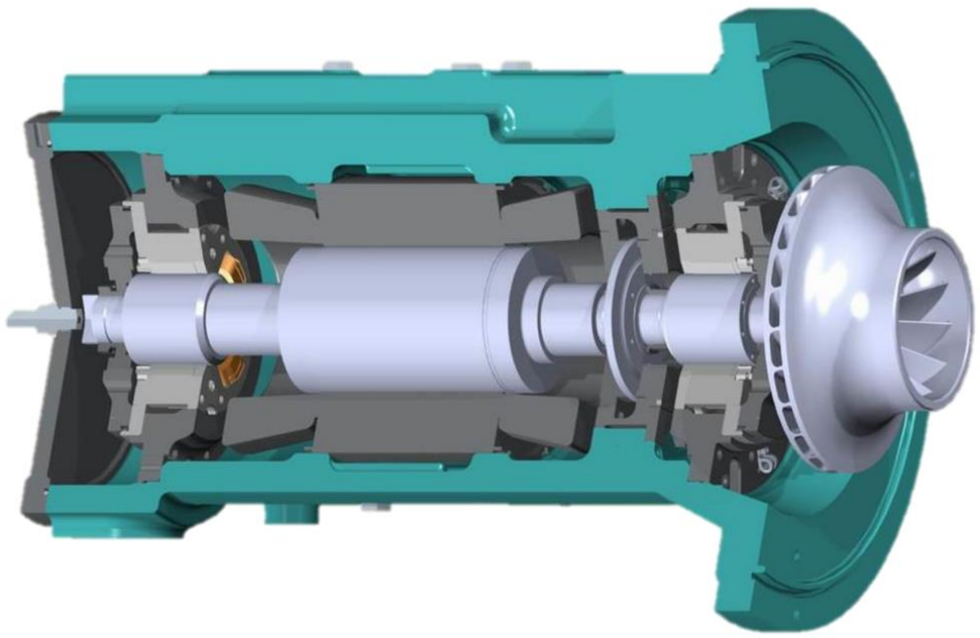


Wennemar, Jurgen (2009).

SwRI®

Compressor sealing and bearing design

- Dry gas and oil seals are viable options, with separation technologies a major factor in choosing between them.
- Magnetic bearings have become adopted from numerous OEMs for centrifugal chillers.
  - Advantages: Hermetically sealed, oil-free designs.
  - Limitations: Less mature for large capacity systems, power outage risks that can disrupt the process.

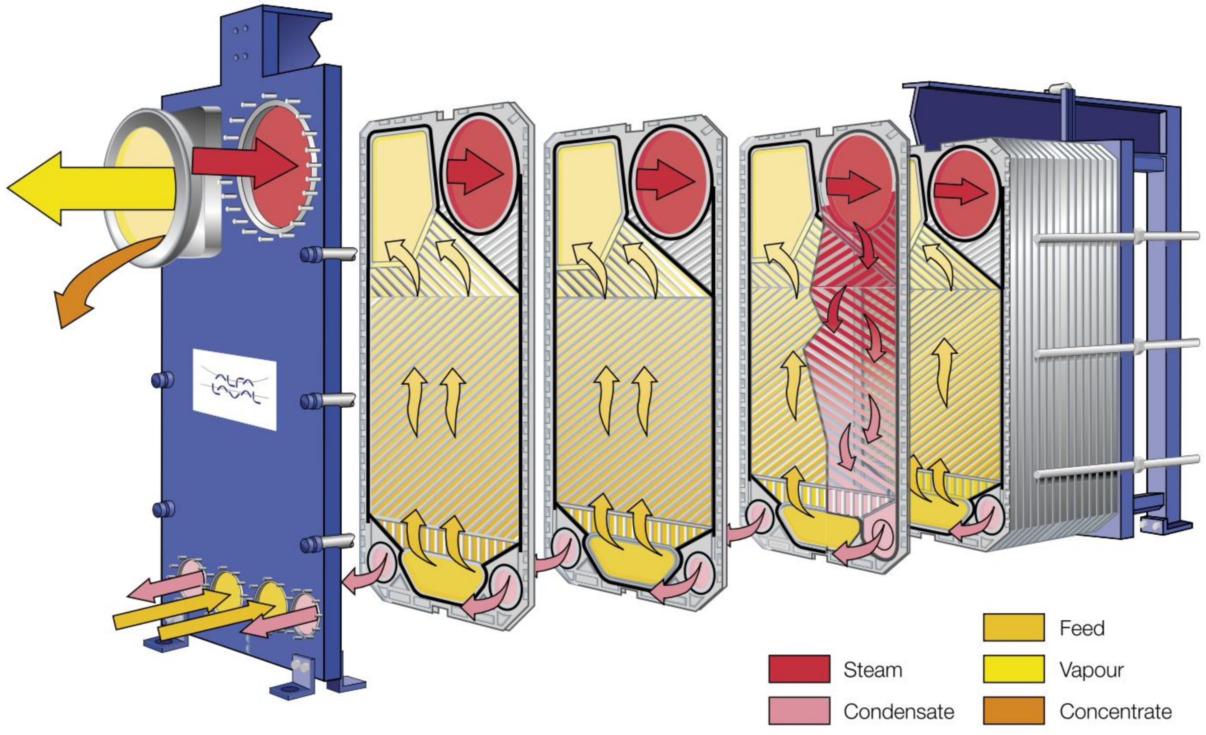


Johnson Controls, York Mag Bearing Compressor

SwRI

Heat Exchangers

- Plate heat exchangers present high performance with low approach temperatures (~2°C).
- An industrial heat pump condenser for steam generation presents unique design challenges:
  - Refrigerant being condensed.
  - Water/steam being evaporated.
- Semi-welded designs or custom gaskets can be required based on refrigerant.
- Diffusion bonded and shell and tube heat exchangers are also options.



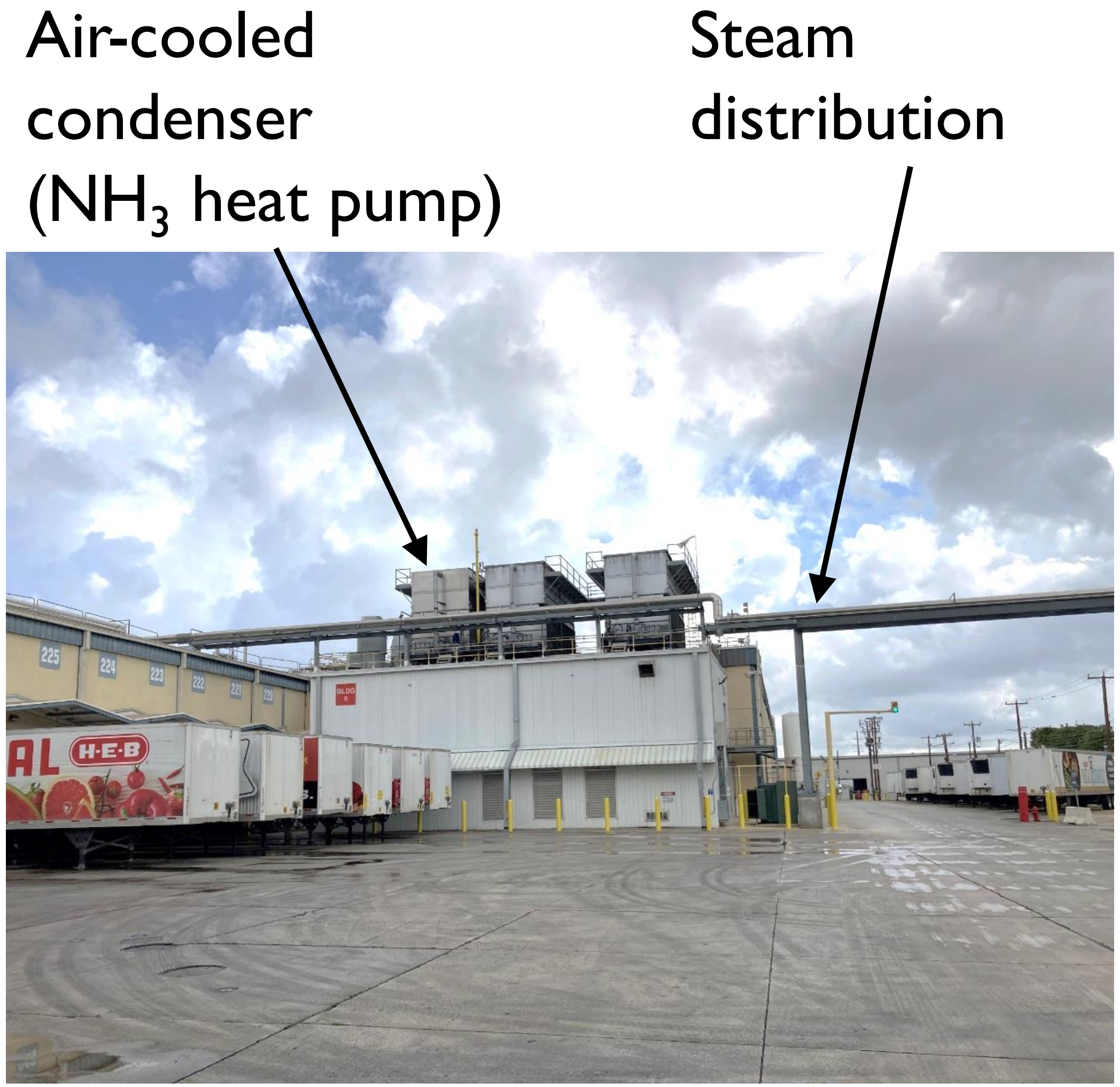
Alfa Laval, AlfaVap Plate Heat Exchanger

Process integration factors

- Required steam conditions may necessitate additional steam compression equipment.
- Evaporator requires customization dependent on waste heat source.
- Compared to a steam boiler, a greater number of variables exist during operation and startup.

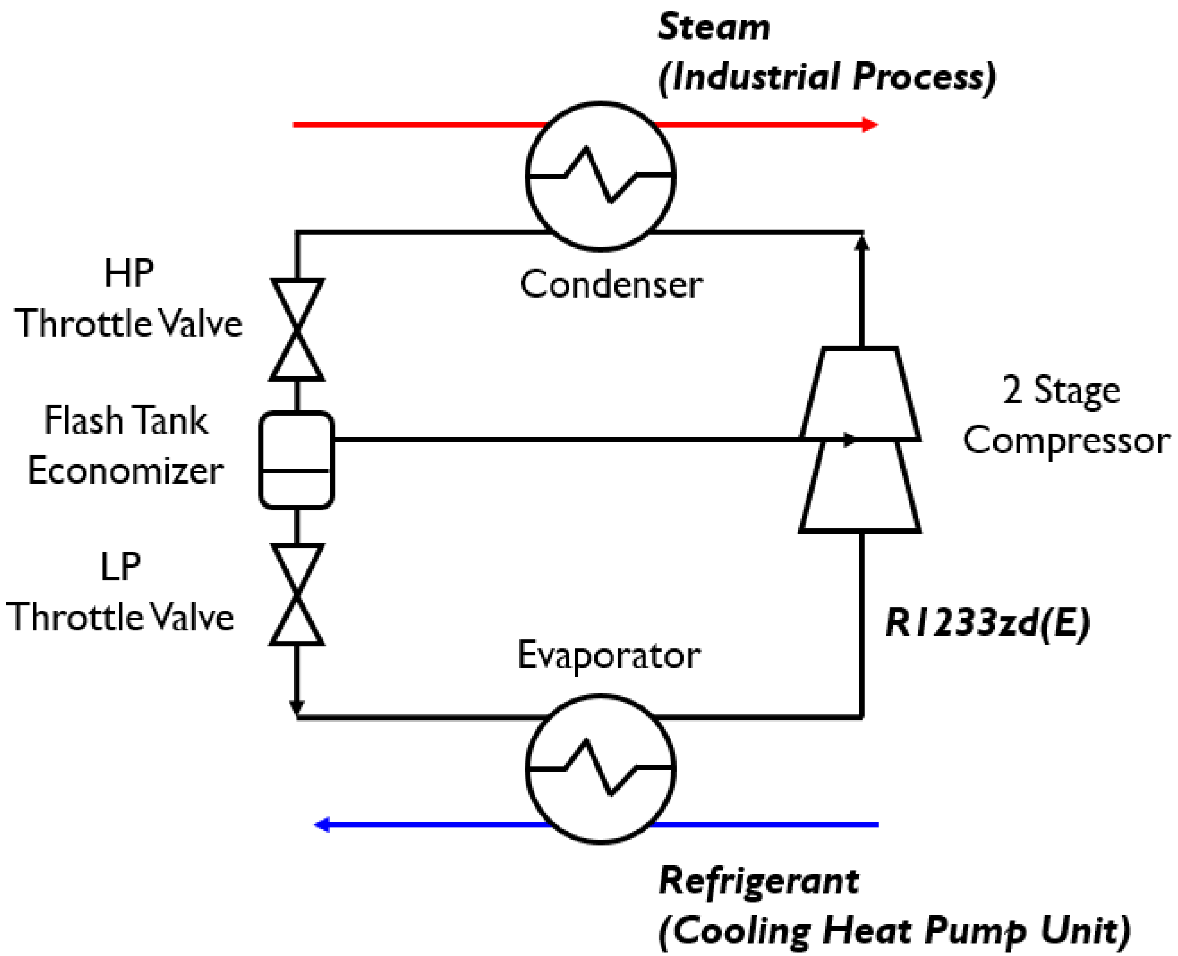
Use case: Dairy pasteurization facility

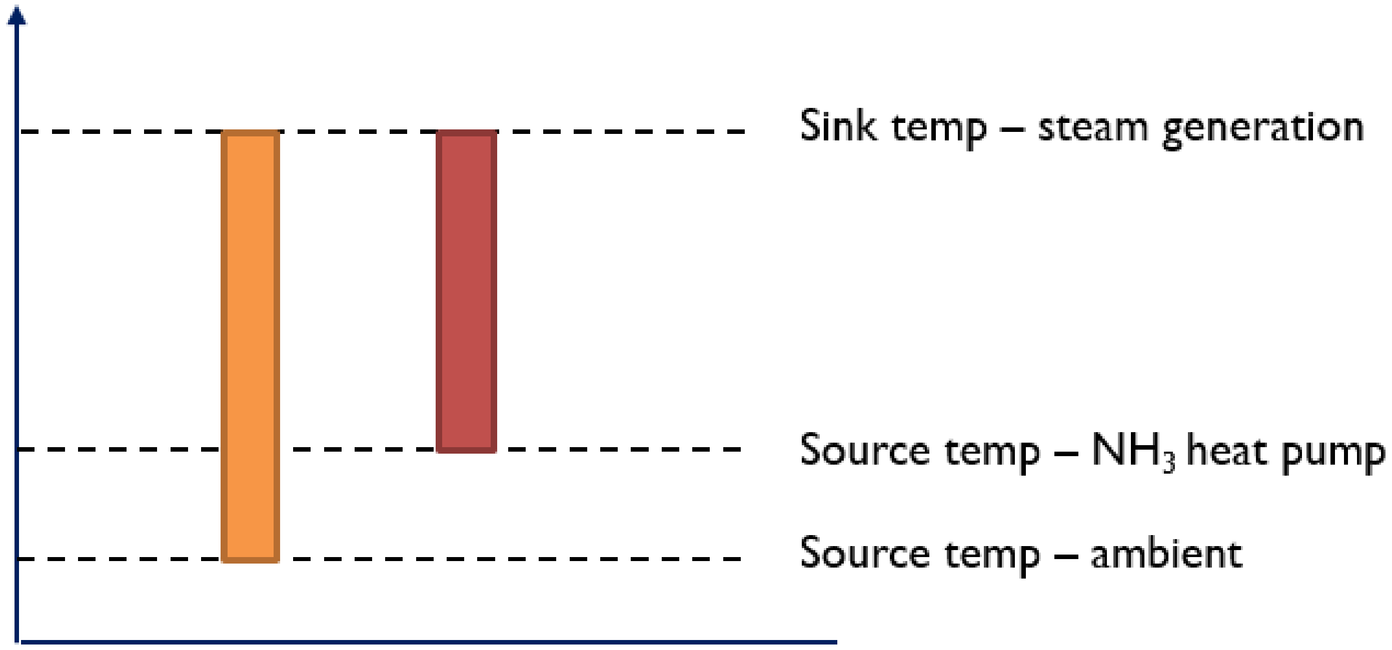
- Ultra-high temperature (UHT) pasteurization involves exposing dairy milk to temperatures of 138°C. The process heat comes in the form of steam.
- Existing infrastructure at a San Antonio dairy plant includes natural gas steam boilers.
- NH_3 heat pumps are used throughout the plant for refrigeration.



SwRI®

Use Case: IHP Architecture

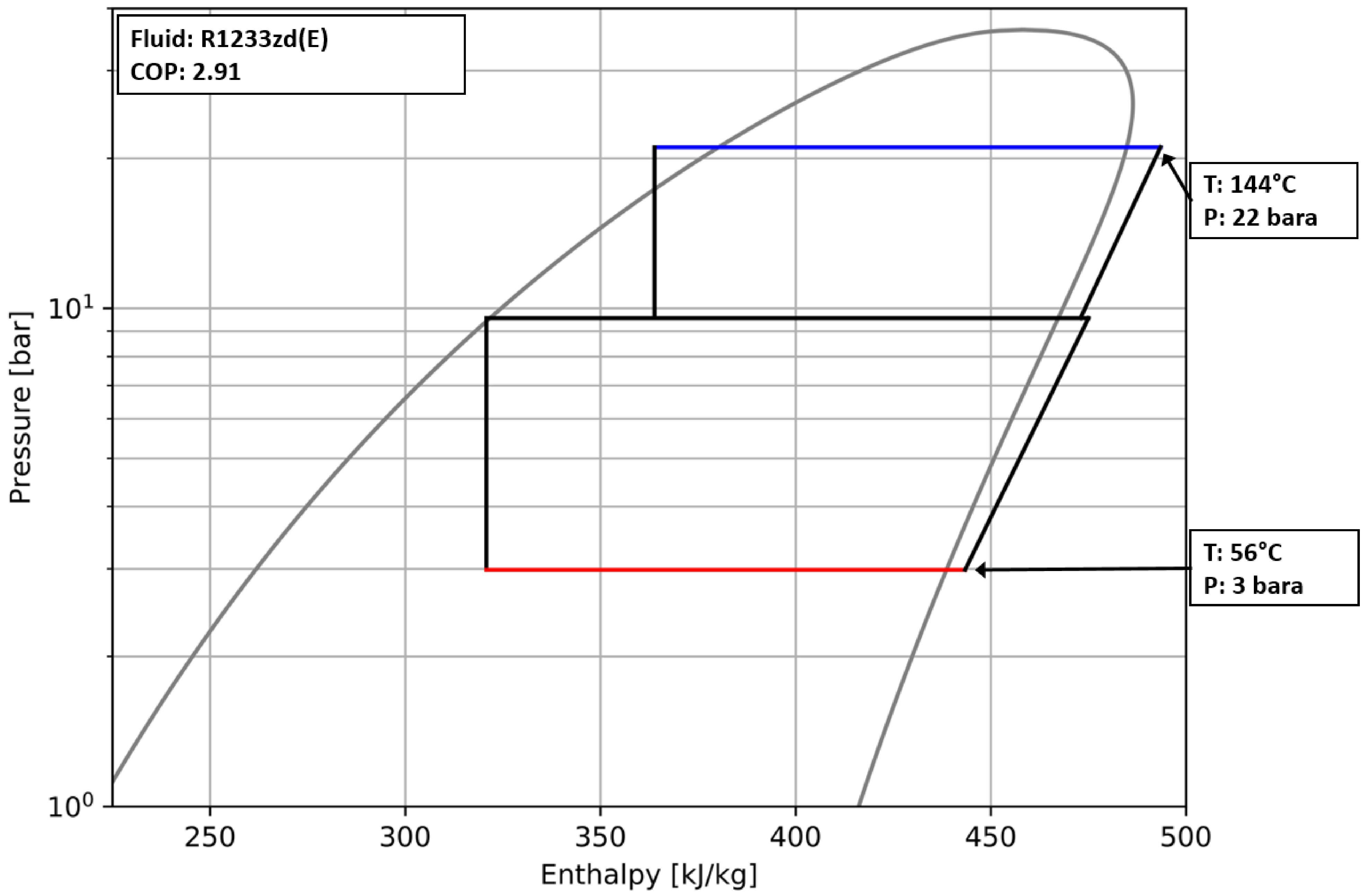




- NH_3 refrigeration heat source makes steam generating IHP possible in a vapor-compression cycle architecture.

SwRI®

Use Case: Thermodynamic cycle perspective

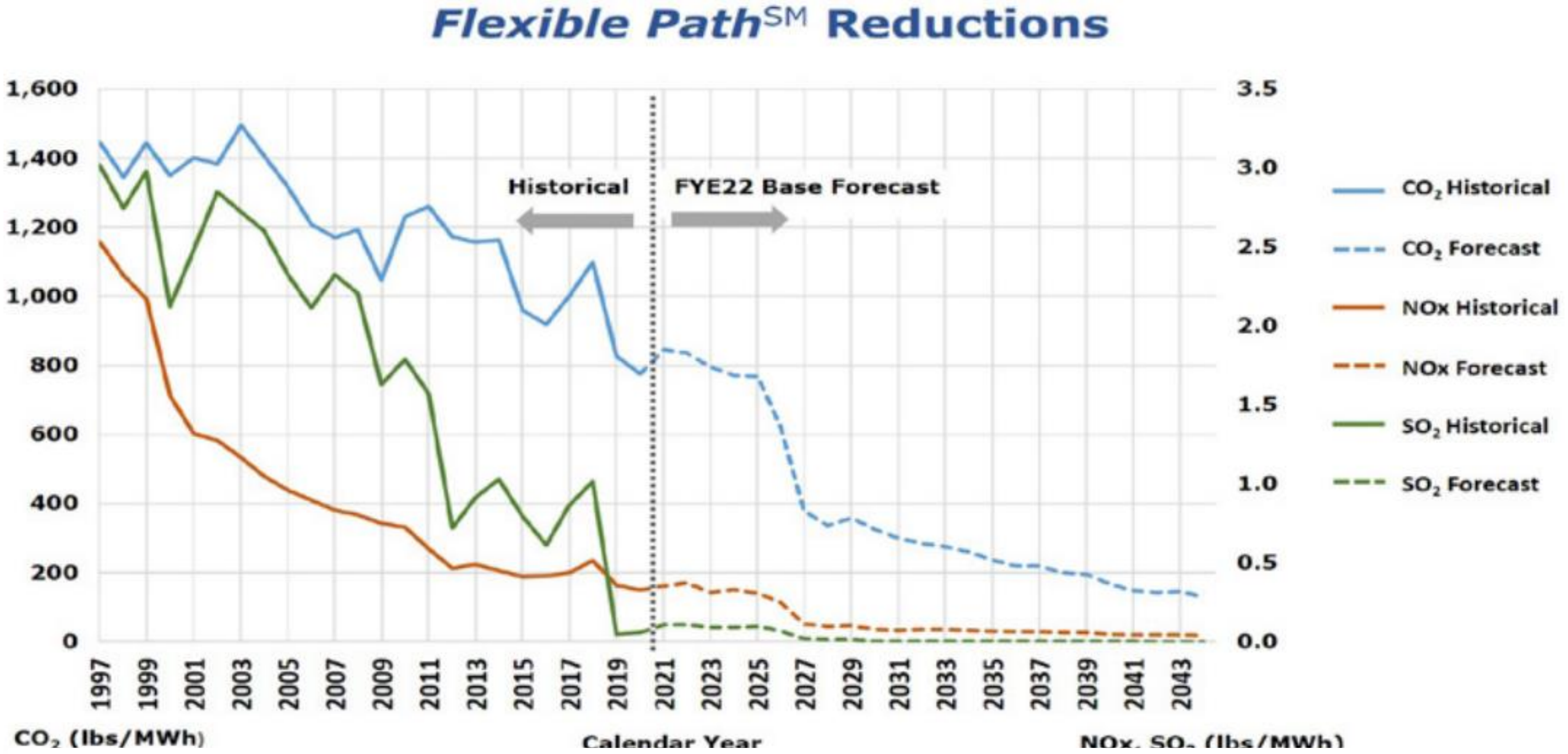


Use Case: Technoeconomic questions

- What level of CO_2 emissions reduction can be achieved?
  - What is the carbon intensity of the power source?
- What payback period can be achieved?
  - How do electricity costs compare with natural gas costs?

Use Case: Carbon intensity of the power source

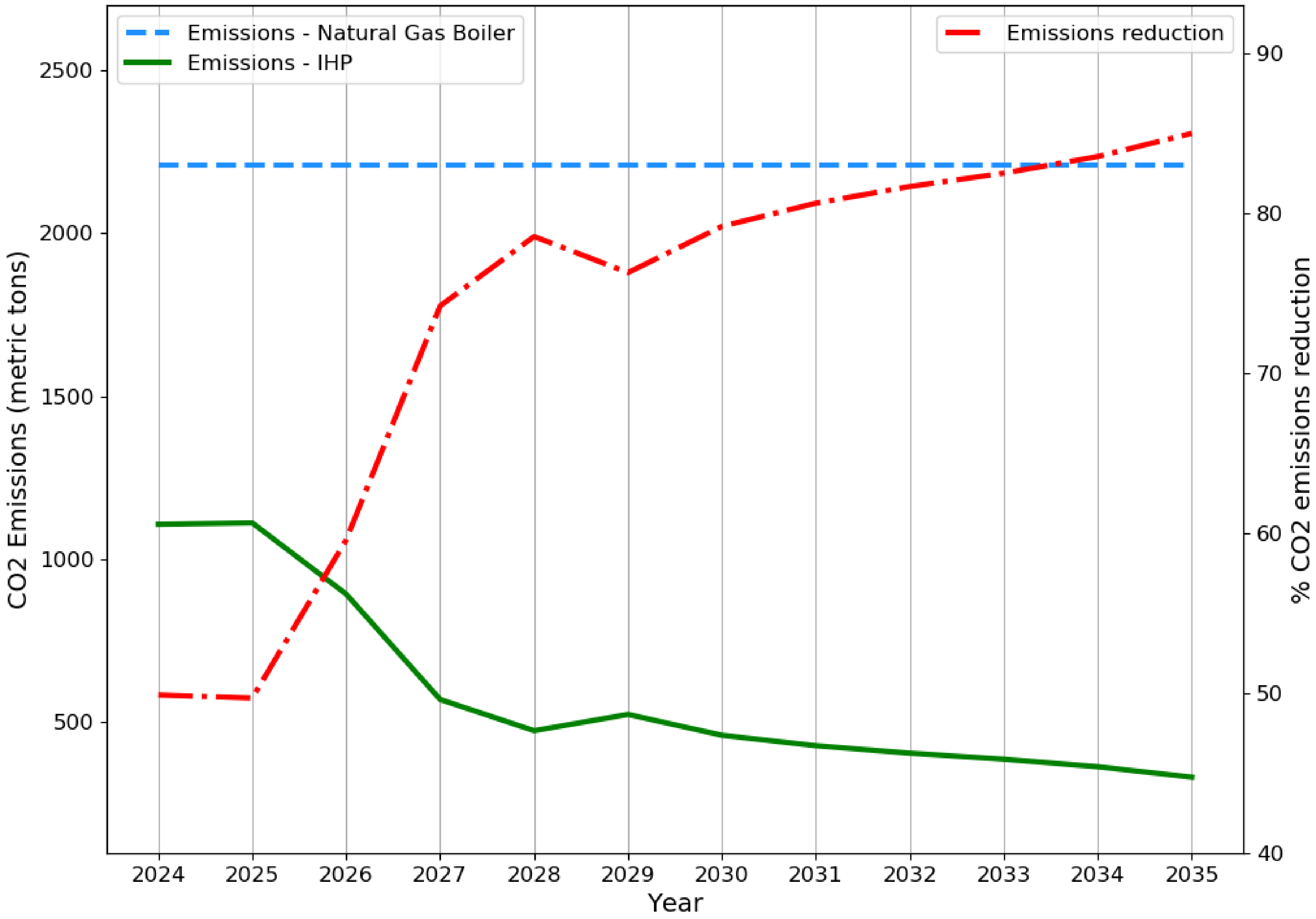
- Over time, increased retrofit from coal to natural gas fired units and increased renewable penetration decreases the carbon intensity of grid power generation.



CPS FY22 Forecast

Use Case: Significant CO_2 emissions reduction possible

- Natural gas boiler assumptions:
  - Thermal efficiency: 80%
  - Energy density: 1037 btu/ft^3
  - Emissions coeff.: .0549 kg CO_2/ft^3
- Industrial heat pump assumptions:
  - COP: 2.91 for equivalent steam thermal output.
  - CO_2 intensity year-to-year from CPS, San Antonio utility.
- 85% emissions reduction by 2035.



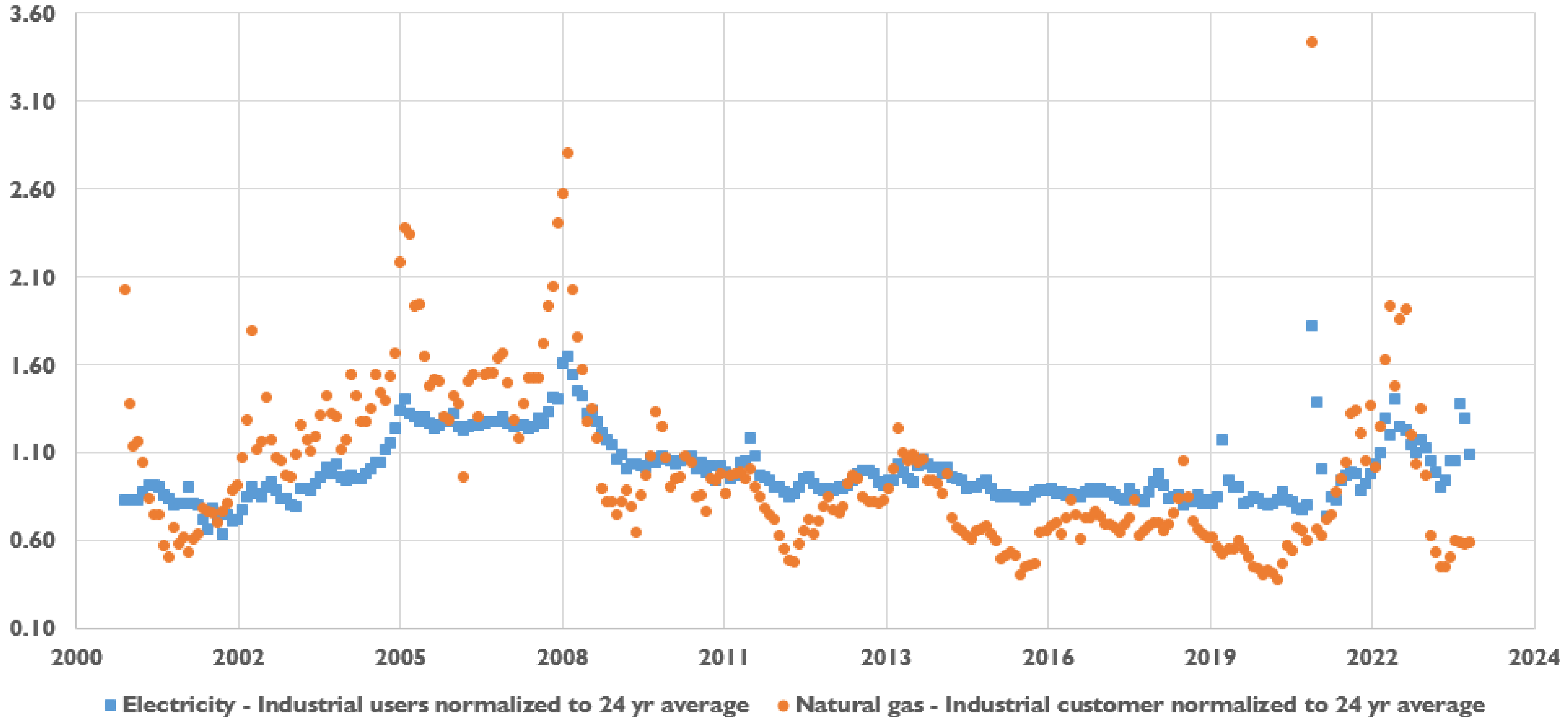
SwRI

Use Case: Economic factors

- CPS industrial user rates:
  - $.049/kWh *electric*
  - $4.15/1000 ft^3 *gas*
- Higher variability in natural gas prices compared to electricity.

Texas Natural Gas Industrial Price (Dollars per Thousand Cubic Feet)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	9.34	6.35	5.24	5.36	4.80	3.89	3.45	3.43	2.62	2.32	3.10	2.66
2002	2.85	2.46	2.82	2.95	3.62	3.51	3.50	3.22	3.52	3.75	4.09	4.22
2003	4.95	5.92	8.29	5.16	5.38	6.53	5.39	4.94	4.87	4.47	4.44	5.01
2004	5.80	5.41	5.10	5.51	6.03	6.57	6.11	5.99	5.17	5.41	7.11	6.56
2005	5.88	5.87	6.21	7.10	6.65	6.44	7.08	7.68	10.08	10.96	10.79	8.92
2006	8.94	7.57	6.82	6.98	6.94	5.99	5.92	6.58	6.34	4.41	6.95	7.13
2007	6.00	7.10	7.14	7.16	7.53	7.68	6.91	5.92	5.45	6.35	7.02	7.03
2008	7.02	7.92	8.90	9.41	11.09	11.87	12.93	9.32	8.12	7.24	5.88	6.22
2009	5.47	4.13	3.77	3.80	3.46	3.78	4.09	3.66	2.97	3.97	4.45	4.98
2010	6.14	5.75	4.96	4.19	4.40	4.41	4.97	4.81	3.91	3.97	3.52	4.39
2011	4.35	4.53	4.01	4.47	4.50	4.56	4.39	4.64	4.17	3.92	3.63	3.45
2012	3.31	2.90	2.55	2.26	2.22	2.66	3.01	3.32	2.92	3.28	3.65	3.90
2013	3.58	3.48	3.65	4.27	4.48	4.38	3.91	3.77	3.80	3.75	3.83	4.11
2014	4.63	5.69	5.05	4.87	5.03	4.82	4.90	4.36	4.35	4.26	3.98	4.50
2015	3.38	3.11	3.01	2.88	2.82	3.04	3.08	3.13	2.95	2.78	2.29	2.38
2016	2.45	2.39	1.88	2.08	2.14	2.16	2.98	3.02	3.15	3.22	2.93	3.35
2017	3.84	3.43	2.81	3.34	3.37	3.51	3.40	3.19	3.21	3.11	2.98	3.21
2018	3.35	3.81	2.89	3.01	3.13	3.25	3.22	3.02	3.21	3.50	3.87	4.86
2019	3.92	3.27	3.05	2.95	2.85	2.84	2.61	2.40	2.55	2.56	2.78	2.54
2020	2.32	2.10	2.04	1.86	1.99	1.89	1.74	2.18	2.64	2.49	3.12	3.03
2021	2.76	15.81	3.06	2.87	3.31	3.45	4.05	4.40	4.81	6.11	6.20	5.57
2022	4.87	6.30	4.67	5.74	7.52	8.90	6.82	8.56	8.81	5.53	4.79	6.23
2023	4.49	2.87	2.47	2.09	2.10	2.35	2.77	2.71	2.67	2.71		



Use Case: Outcomes

- Energy savings of 11% for the equivalent steam thermal output from the IHP.
- Replacement of existing steam boiler would be 10+ year payback period.
- Use of IHP for new installation can have attractive payback period compared to natural gas boiler, dependent on unit cost.

Payback period	Cost of IHP ($/kWth)	Cost of Boiler ($/kWth) *(Rissman, 2022)*
2	263	234
4	286	234
6	305	234
8	320	234

Conclusions

- Innovation with industrial heat pumps can open up market possibilities for steam generation.
- Current compression technology is feasible for high temperature lift requirements, but more development is needed.
- Performance is paramount to making an economic case for steam generating IHP.
  - High critical temperature refrigerant for latent heat transfer.
  - Energy efficiency improvements for the facility, not just process heat.
  - Condensing turbines are a future area for development.
- Decarbonized power sources drive emissions reductions.