High Temperature (Industrial) Heat Pumps: An Untapped US Industrial Process Energy Efficiency Opportunity

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Low Temperature Industrial Processes Workshop
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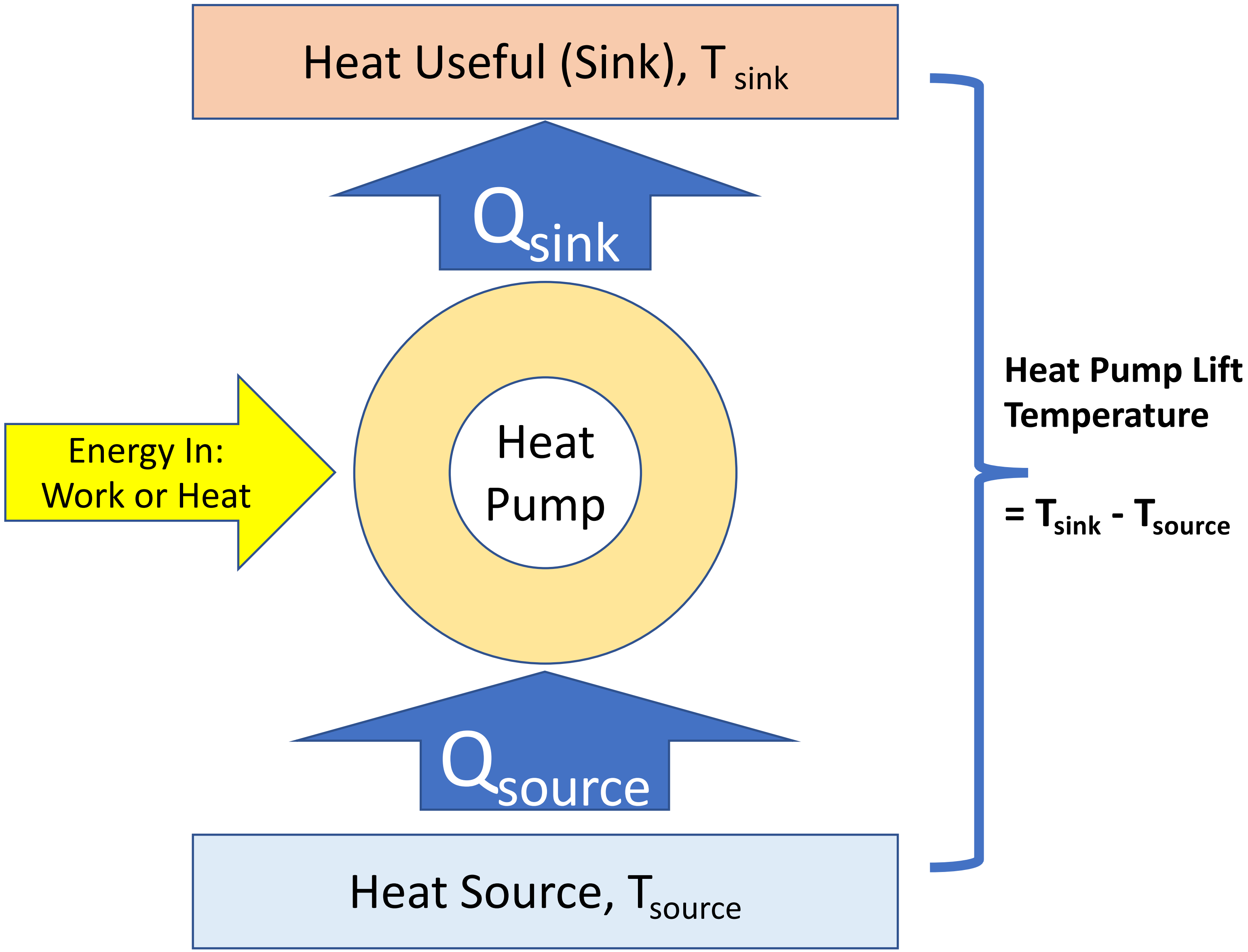
Fundamentals of Heat Pumps



$$COP_{heating} = Q_{sink}/\text{Energy In}$$

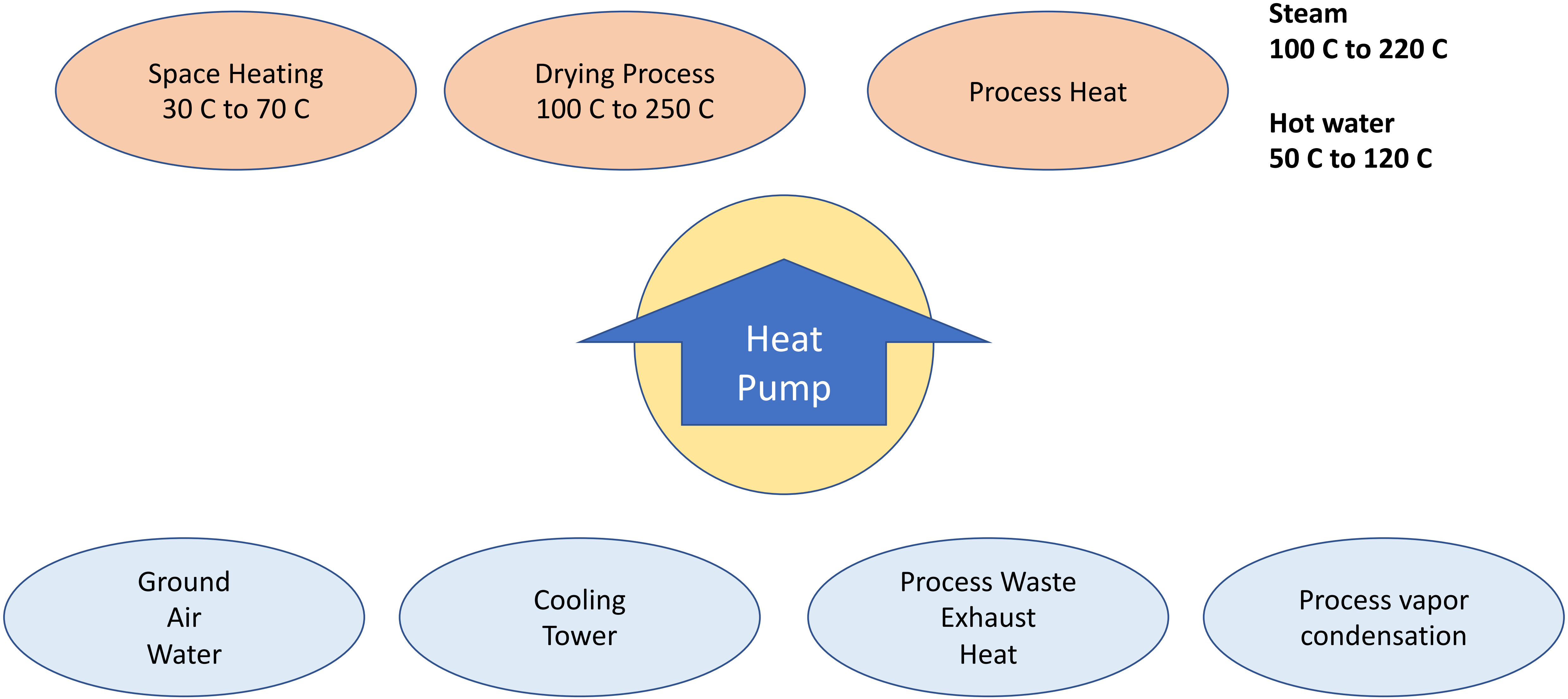
$$COP_{carnot,\ heating} = T_{sink} / (T_{sink} - T_{source})$$

$$COP_{heating} = \text{Carnot Eff.} * COP_{carnot,\ heating}$$

Heat pump Carnot Eff. ranges from ~30 - 60%

Less lift temperature equals greater heat pump efficiency

Typical HTHP heat sources and sinks



US DOE Heat Pump Program & IEA Annex 21 Study

IEA Annex 21 Study (1993 – 1995)

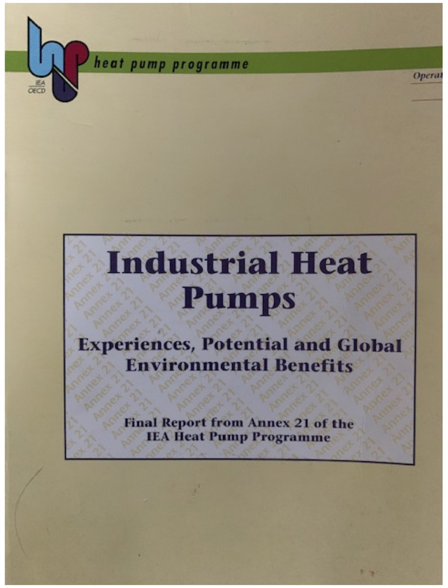
- Industrial Heat Pumps: Experiences, Potential and Global Environmental Benefits

- 8 countries collaborated
- 35 processes evaluated for IHP potential across all 8 countries
- Each country performed IHP market study (see right hand box for US IHP Study)

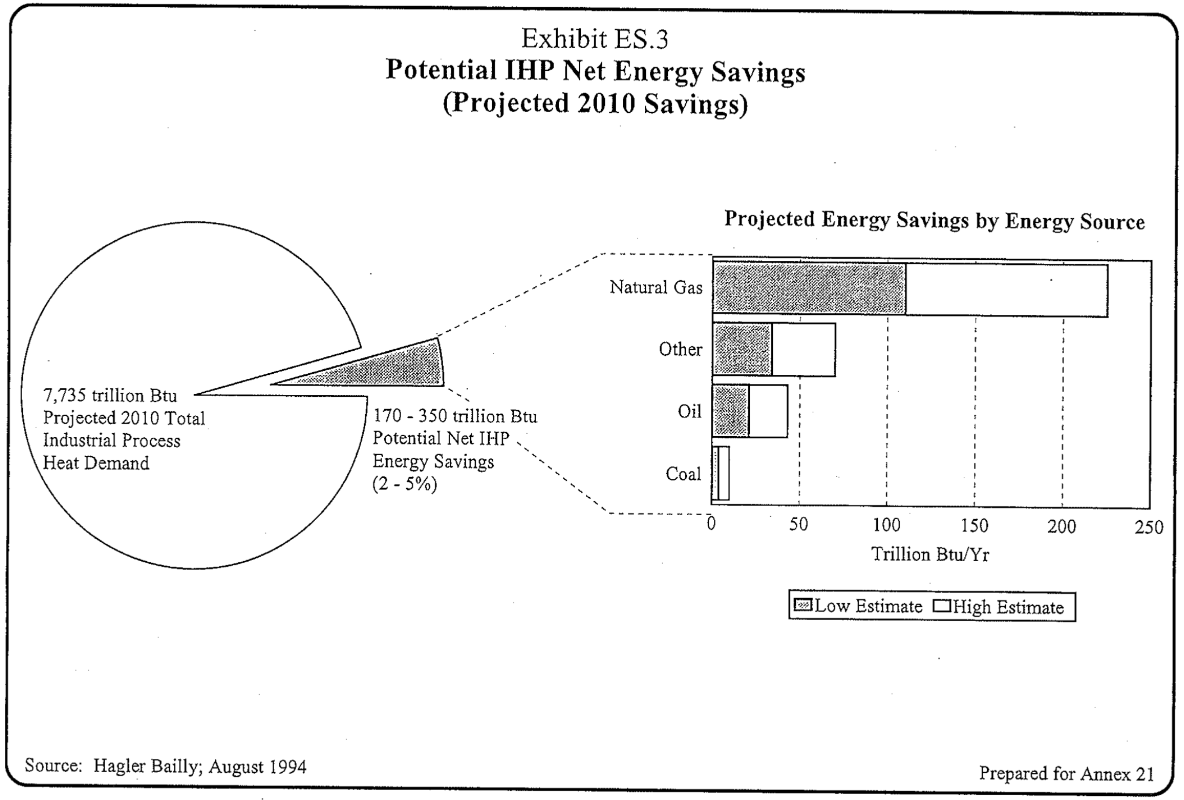
US IHP Market Study

- US study screened 42 processes; 26 found for economic IHP potential
- 8 processes accounted for most (68%) of IHP economic energy savings
  - Corn milling
  - TMP pulp
  - Unbleached kraft linerboard
  - Beet sugar refining
  - Bleached kraft pulp
  - Bleached kraft pulp and paper
  - High fructose corn syrup
  - Synthetic rubber

https://heatpumpingtechnologies.org/annex21/



US DOE 1995 Industrial Heat Pump Market Study found 2-5% net process heat savings; 170 - 350 TBtu/yr



Average Industrial Energy Prices	1995 (2019$)	2019
Natural Gas ($/MMBtu)	$6.56	$3.85
Electricity Price (cts/kW-hr)	4.28 cts	6.83 cts
Electricity Price ($/MMBtu)	$22.16	$20.00
Electricity/Gas Price Ratio	3.37	5.19

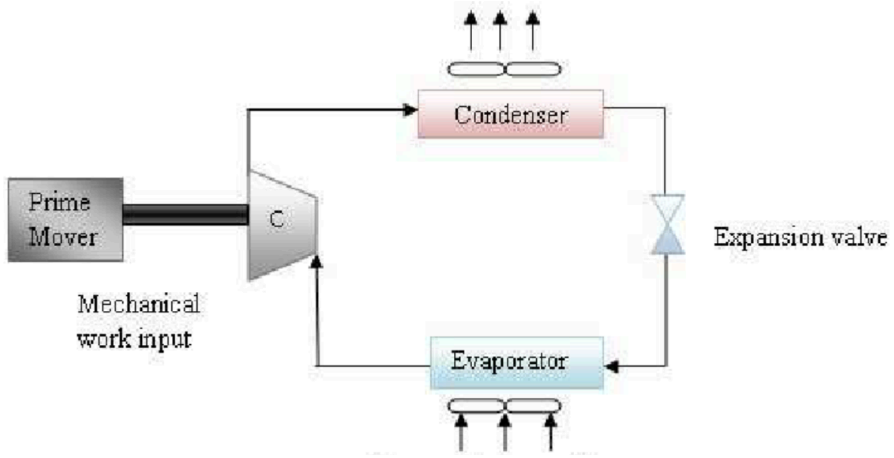
Study 1995 Energy Prices

Recent energy prices are lower than in 1995

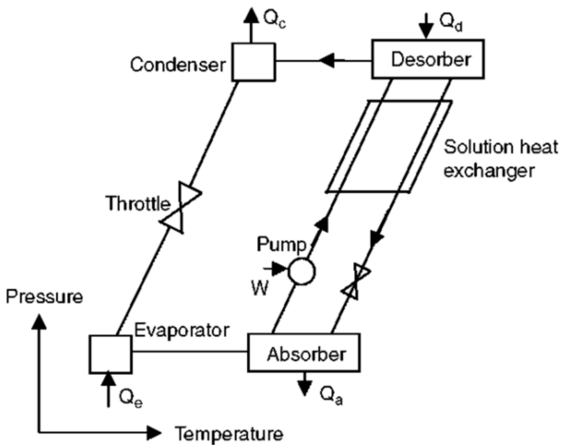
Annex 21 Global Environmental Benefits of IHPs: US Study, Prepared for US DOE & EPRI by RCG Hagler Bailey, Aug 1994

4 High Temperature Heat Pump Types

Cycle Type	High Temperature Heat Pump Type
Closed Cycle	Mechanical vapor compression heat pump
Closed Cycle	Heat activated heat pump: absorption or heat transformer
Open Cycle	Mechanical vapor re-compression (MVR) heat pump
Open Cycle	Thermal vapor re-compression (TVR) or steam ejector heat pump

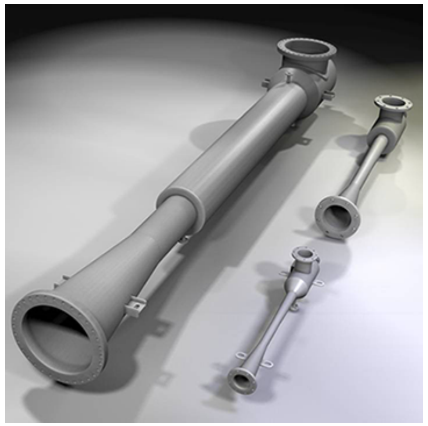


Closed Cycle Mechanical Vapor Compression Heat Pump



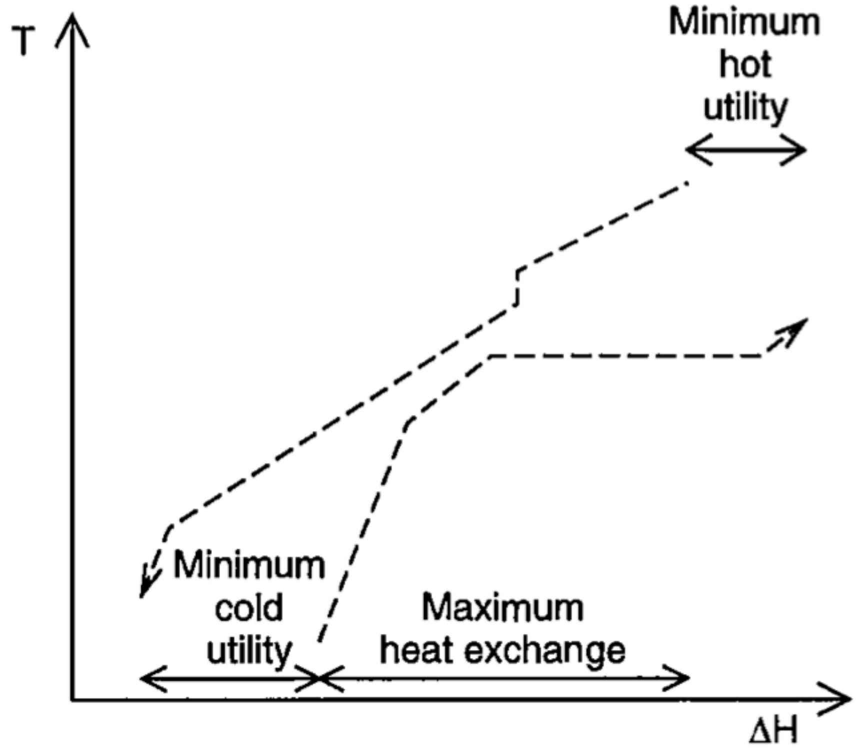
Absorption heat pump

Mechanical vapor recompressor

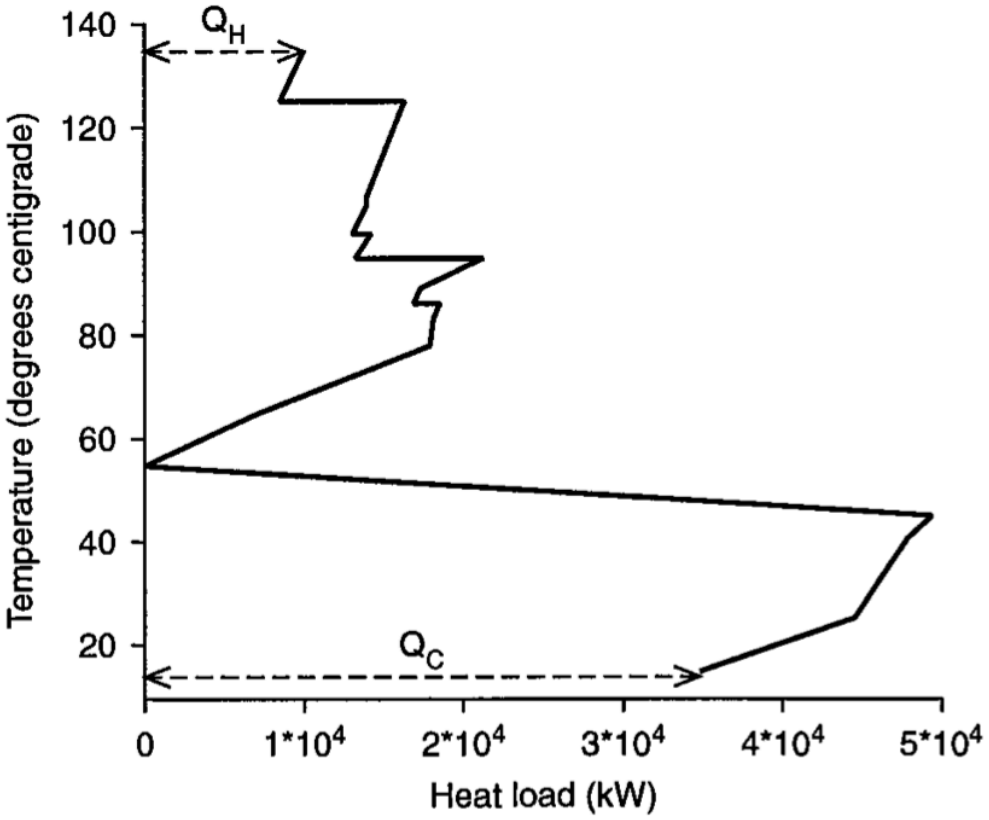


Steam ejector

Heat Integration and Proper Placement of HTHPs with PINCH technology

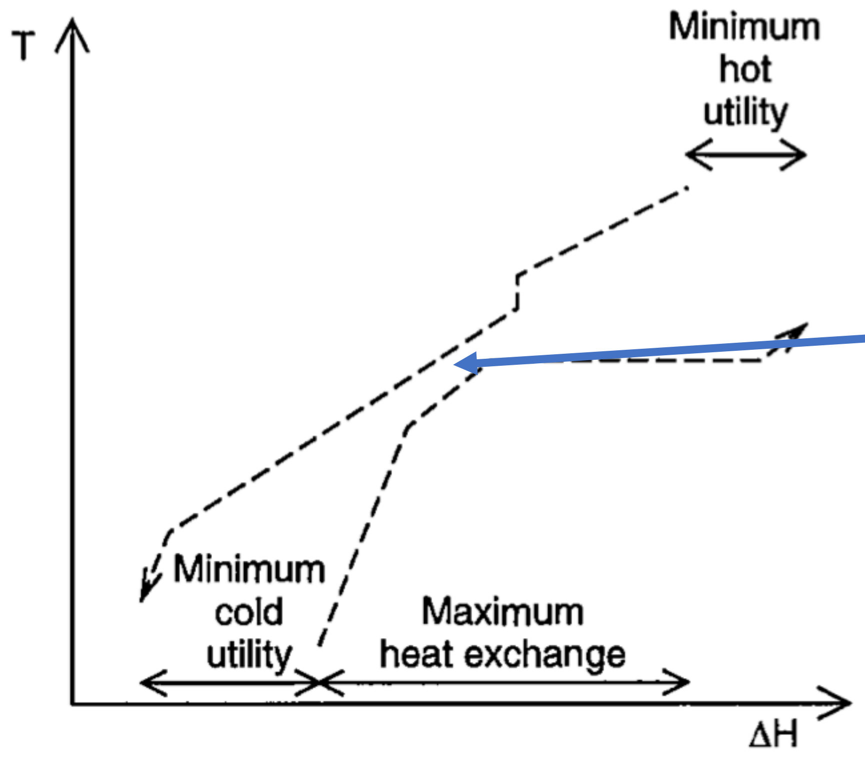


Example Composite curves of heating and cooling streams



Example Grand Composite Curve

Heat Integration and Proper Placement of HTHPs with PINCH technology



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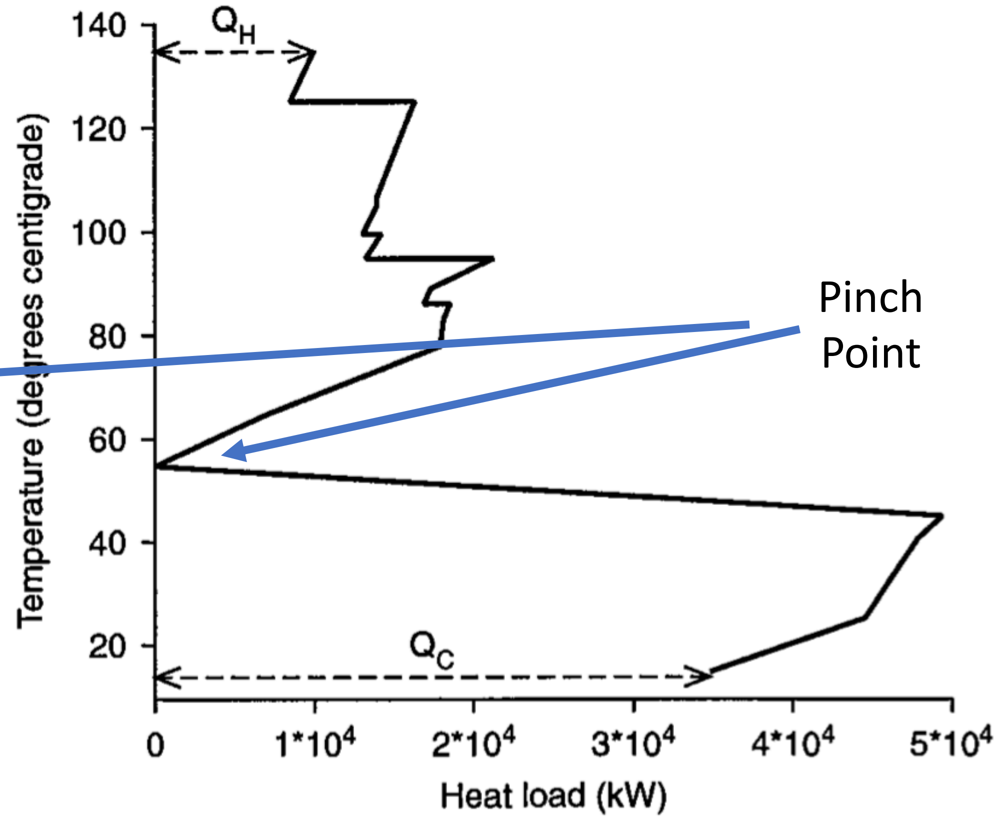
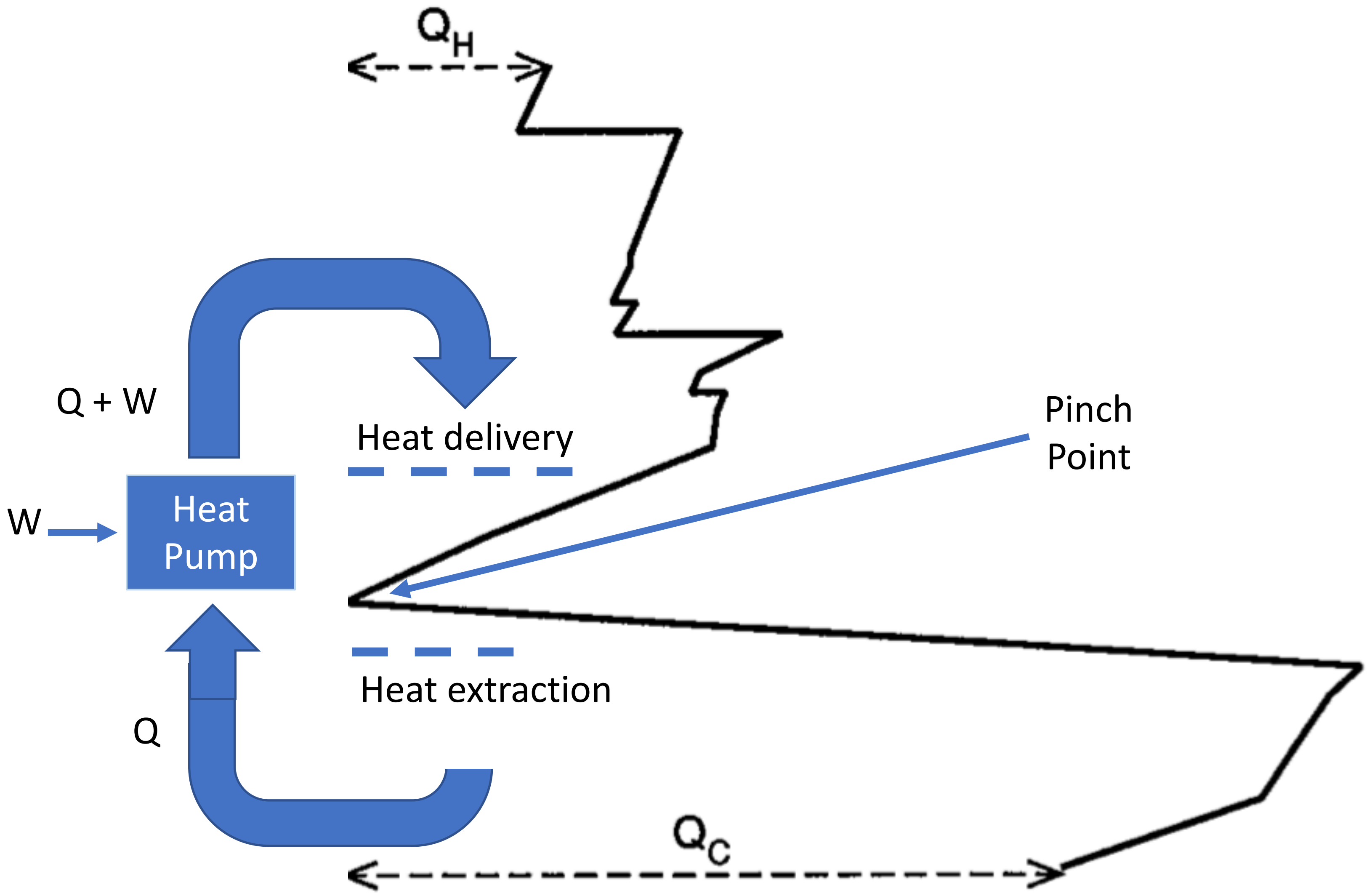


Example Grand Composite Curve

Heat Pump should pump heat around pinch point



Key IHP barriers in the US

Low level of awareness of the technical possibilities and economic feasibility among end users, engineering firms, suppliers, etc.

Lack of knowledge on how to integrate heat pumps into existing industrial processes

Lack of best practice examples to create trust in new type of process heating solution

Most times one-off, tailor-made design and many times need to be integrated to process

Long payback on investment due to low natural gas price and/or high electric to natural gas price ratio

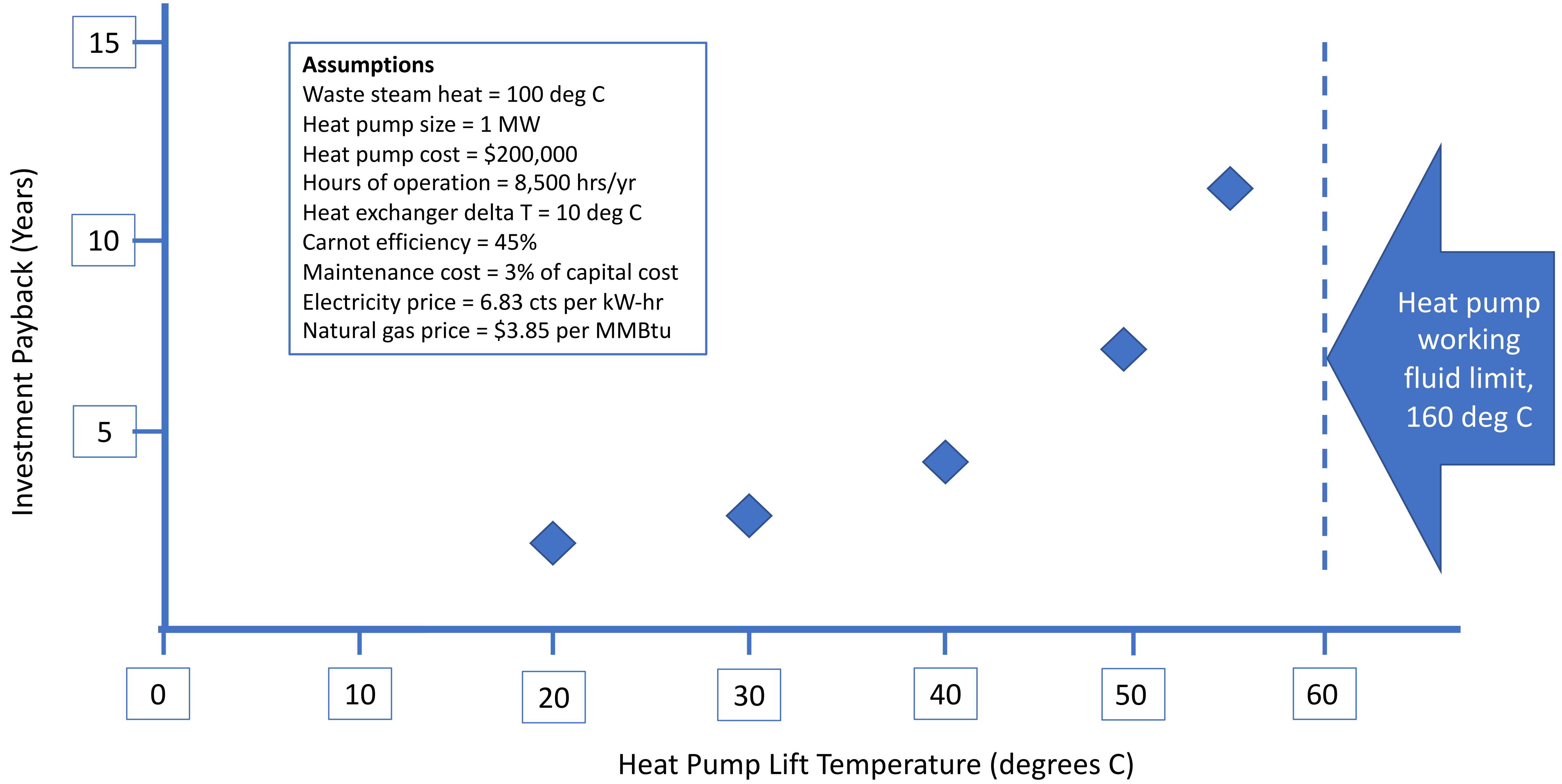
Competing process heating energy efficiency options

Heat storage could be required

Existing technology limited by heat pump output temperature (~160 deg. C, 320 deg. F)

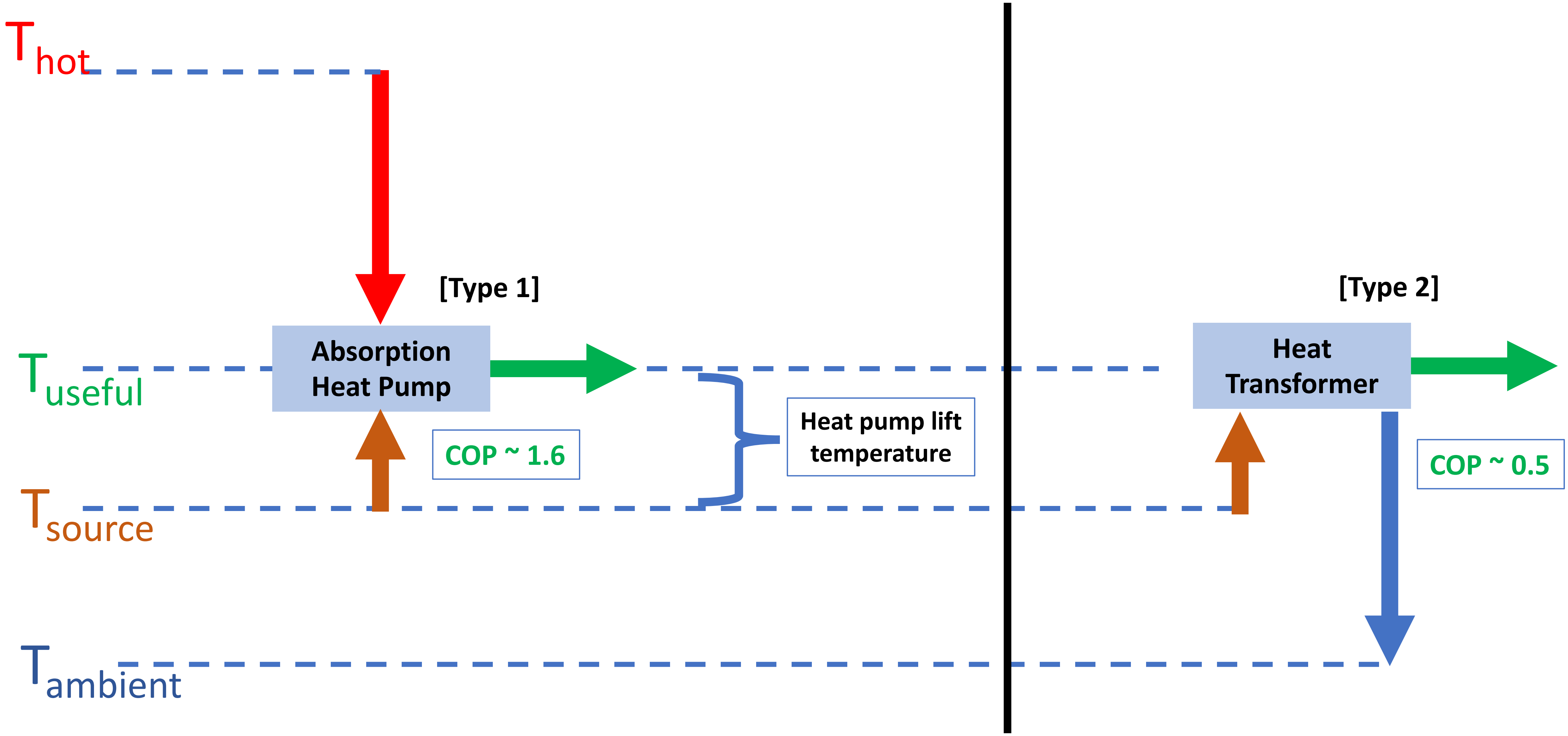
Limited domestic equipment suppliers – EU, Japan

Mechanical Vapor Compression Heat Pump Payback versus Heat Pump Lift Temperature



What are major technology opportunities that are NOT currently being researched?

Advanced High Temperature Heat-Activated Heat Pumps – Type 1 and 2



Example Economics for 1 MW Heat Transformer

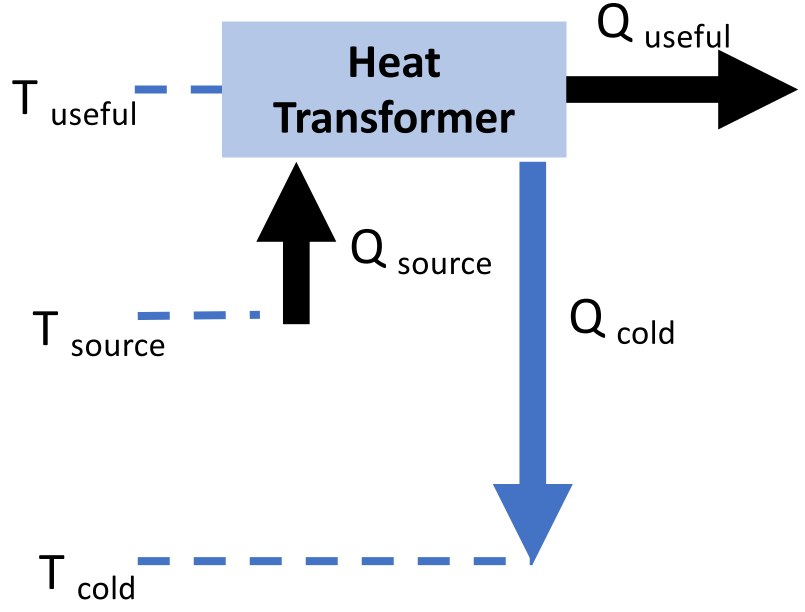
Q sink = 1 MW @ T sink = 150 deg. C (steam)
Q source = 2 MW @ T source 100 deg. C (steam)
Q cold = 1 MW @ T cold = 30 deg. C
Heat Transformer Cost = $1.5 Mil **($1,500 per kW, pilot unit)**
Annual maintenance cost = 2% of 1.5 Mil = $30,000 per year
Electricity requirements = 40 kW
Electricity price = 6.83 cts per kW-hr
Operating hours = 8,760 hrs per year
Annual electricity cost = $24,000 per year
Total operating cost = $54,000
Natural gas cost = **$3.85 per MMBtu (avg. US industrial price, 2019)**
Steam cost = $5.90 per 1000 lb steam
Steam cost savings[1] = $194,000 per year

Payback = $1,500,000 / ($194,000 - $54,000) = 10.7 yrs

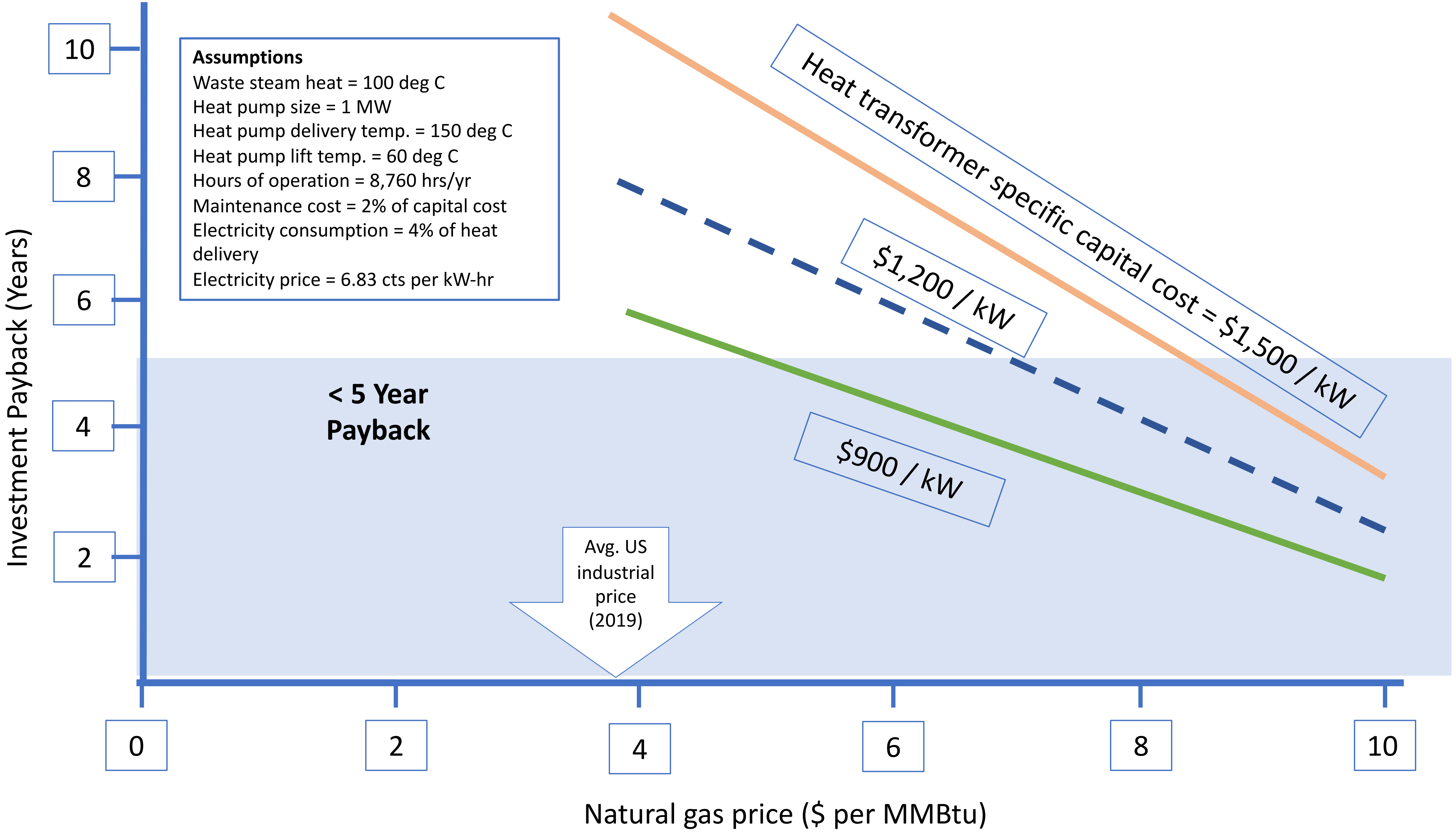
Note 1 – assume 1MW Heat Transformer produces 3750 lbs steam per hr @ 150C and avoids boiler steam and cooling tower costs @ $5.90 per 1000 lbs steam. Boiler steam costs account for energy cost (natural gas cost and boiler combustion efficiency) and chemical cost needed to treat boiler water.
Private communication Riyaz Papar, January, 2021

$$COP \sim 0.5$$

$$T_{useful} - T_{source} <= 0.8 * (T_{source} - T_{cold})$$



Heat Transformer Payback versus Natural Gas Price



Emerging heat-activated heat pump technology

QPinch

Heat-activated heat pump by reversible chemical reaction

phosphoric acid to diphosphoric and water

$$H_4P_2O_7 + H_2O \rightleftharpoons 2H_3PO_4$$

T_{sink} up to 220 deg. C

Minimal electricity requirements; waste heat-driven

Lift temperature= 40 - 100 deg. C

Multi megawatt demos planned; independent validation needed for:

- Cost and performance
- Reliability and material durability
- Impact on process control

QPINCH

www.qpinch.com

What are the most critical research priorities in HTHPs?

- **Heat-activated heat pumps R&D should focus on:**

➢ Developing various Type 1 and 2 cycles and configurations to demonstrate performance and cost
➢ Demonstrate heat pump material durability in actual industrial settings and conditions.
➢ Demonstrate heat pump operability and reliability in varied industrial processes to prove out economics
➢ Prove heat pump working fluids are safe and environmentally benign

- **Technology development R&D targets**

➢ Specific capital cost (total installation) < $1,000 per kW
➢ Heat delivery > 200 deg. C and ideally > 250 deg. C
➢ Lift temperature up to 100 deg. C

Conclusions

There's reason to be optimistic about High Temperature Heat Pumps

1. **New perspective by industry:** Companies that are serious about decarbonizing their energy footprints will consider HTHPs if they yield significant (>5 – 10%) energy savings and decarbonization at a reasonable payback, e.g., less than 5 years.

2. **R&D justified to build domestic High Temperature Heat Pump industry:** Advanced heat-activated heat pumps could be a game-changer to greatly expand the number of economic opportunities in the US process industries - - even with only modest increases in natural gas prices. Cost-shared R&D in the US should help build the domestic supplier base for high temperature heat pumps.

3. **Technology development is not enough:** Further technology development is needed and justified but needs to be coupled with effective energy policy and/or incentives to motivate all participants in HTHP market – end users, vendors, engineering firms and energy efficiency program administrators/utilities.

Background Slides

Mechanical vapor compression heat pumps; reference Cordin Arpagaus, 2020

Supplier update – market overview

NTB
Interstate University of Applied Sciences of Technology Buchs
University of Applied Sciences of Eastern Switzerland

Selection of industrial heat pumps with heat supply temperature ≥ 90 °C

Manufacturer	Country	Product	Refrigerant	Max. T_{Supply}	Heating capacity	Compressor type
Kobe Steel (Kobelco steam grow heat pump)		SGH 165 SGH 120 HEM-HR90,-90A	R134a/R245fa R245fa R134a/R245fa	165 °C 120 °C 90 °C	70 – 660 kW 70 – 370 kW 70 – 230 kW	Double screw
Viking Heating Engines AS		HeatBooster HeatBooster S4	R1336mzz(Z) R245fa	160 °C 130 °C	28 – 188 kW 92 – 172 kW	Piston (4 parallel)
Ochsner		IWWDSS R2R3b IWWDS ER3b IWWHS ER3b	R134a/ÖKO1 ÖKO1 (R245fa) ÖKO1 (R245fa or R1233zd)	130 °C 130 °C 95°C	170 – 750 kW 120 – 400 kW 60 – 640 kW	Screw (TWIN unit upto 1,5 MW)
Frigopol (& AIT)		HighButane 2.0	R600	130 °C	50 kW	Piston
Hybrid Energy		Hybrid Heat Pump	R717 (NH_3)	120 °C	0.25 – 2.5 MW	Piston
Mayekawa		Eco Sirocco Eco Cute Unimo	R744 (CO_2) R744 (CO_2)	120 °C 90 °C	65 – 90 kW 45 – 110 kW	Screw
Combitherm		HWW 245fa HWW R1234ze	R245fa R1234ze(E)	120 °C 95 °C	62 – 252 kW 85 – 1301 kW	Piston
ENGIE (ex-Dürr thermea)		Thermeco$_2$ HHR	R744 (CO_2)	110 °C	45 – 1'200 kW	Piston (up to 6 parallel)
Oilon		ChillHeat P60 bis P450	R134a R1234ze(E)	100 °C	30 – 1'000 kW	Piston (up to 6 parallel)
Friotherm		Unitop 22 Unitop 50	R1234ze(E) R134a	95 °C 90 °C	0.6 – 3.6 MW 9 – 20 MW	Turbo (two-stage)
Star Refrigeration		Neatpump	R717 (NH_3)	90 °C	0.35 – 15 MW	Screw (Vilter VSSH 76 bar)
GEA Refrigeration		GEA Grasso FX P 63 bar	R717 (NH_3)	90 °C	2 – 4.5 MW	Double screw (63 bar)
Johnson Controls		HeatPAC HPX HeatPAC Screw Titan OM	R717 (NH_3) R717 (NH_3) R134a	90 °C 90 °C 90 °C	326 – 1'324 kW 230 – 1'315 kW 5 – 20 MW	Piston (60 bar) Screw Turbo
Mitsubishi		ETW-L	R134a	90 °C	340 – 600 kW	Turbo (two-stage)
Viessmann		Vitocal 350-HT Pro	R1234ze(E)	90 °C	148 – 390 kW	Piston (2 to 3 in parallel)

cordin.arpagaus@ost.ch

Ratio of Industrial electricity/gas Price

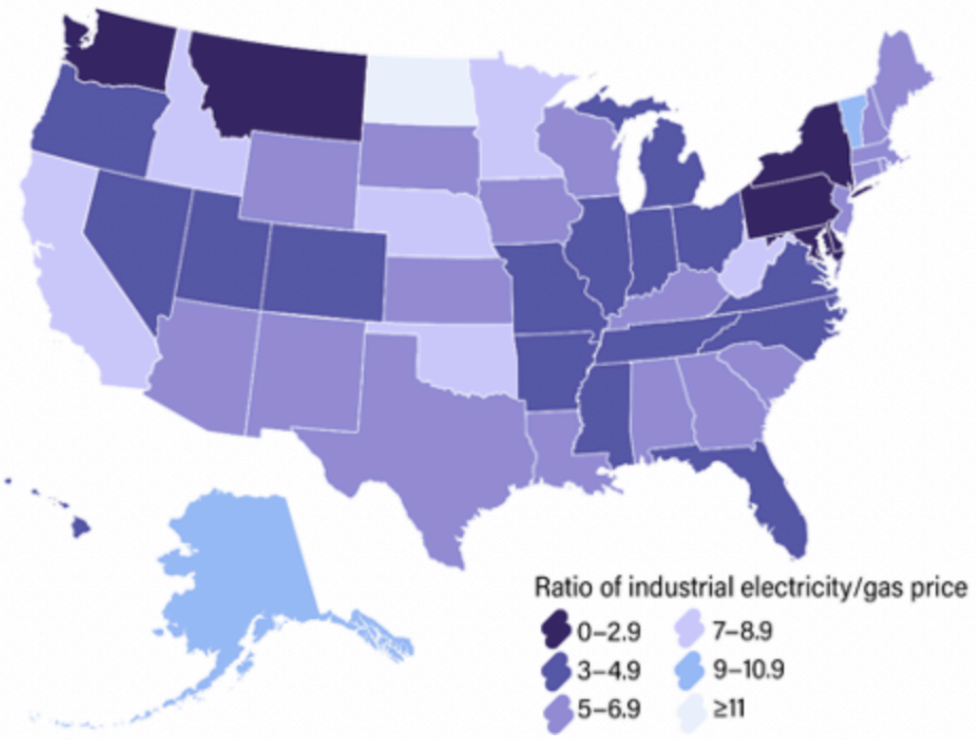
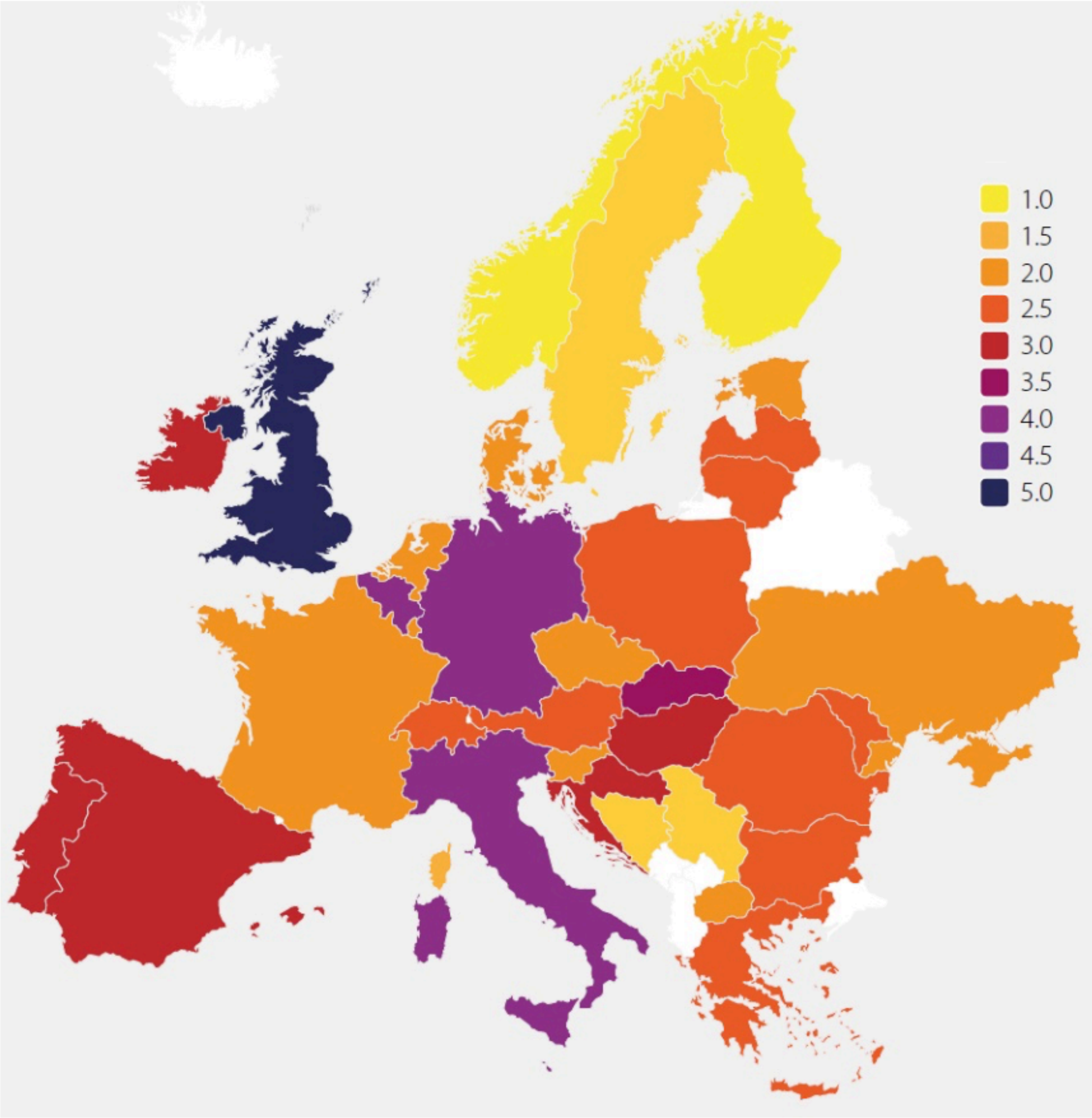


Figure 11. Ratio of industrial electricity to gas price by state. Calculation based on average annual electricity prices and Henry Hub natural gas prices within states. ***Sources:*** **EIA 2020b, 2020e.**

Rightor, Whitlock, Elliott ACEEE 2020

Market challenges

Electricity to gas price ratio



For small scale industrial end-users with
2 GWh/a to 20 GWh/a electricity
3 GWh/a to 28 GWh/a gas

IHP types: Pros and Cons. What are the pros and cons of various HTHP types?

Type	Prime Mover	Pros	Cons	Typical COP
Closed cycle compression	Electricity (Motor) or Fuel (Heat Engine)	- Good COP for moderate lift temperature - Multiple vendors - Electricity only on site	- Requires low electric-fuel price ratio - Limited supply temperature to ~320F supply	3 to 10
Heat-activated (Type 1)	Fuel (Process Heat or Steam)	- Uses lower cost fuel as driver - Minimal moving parts - Higher supply temperature ~400F	- High CapEx - Limited vendors - Emerging technology	1.6
Heat-activated (Type 2)	Waste heat	- Uses free waste heat as driver - Minimal moving parts - Higher supply temperature ~400F	- High CapEx - Limited vendors - Emerging technology - Requires cold sink T Δ	0.5
MVR	Electricity (Motor) or Fuel (Heat Engine)	- Good COP for moderate lift temperature - Electricity only on site	- Requires low electric-fuel price ratio - High speed compressor	3 to 10
TVR	Steam	- Low CapEx - Simple and low maintenance	- Low energy efficiency	2.0