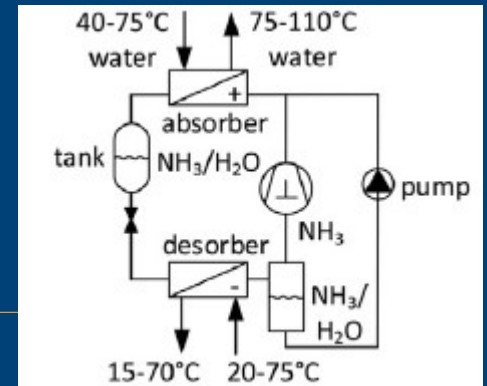
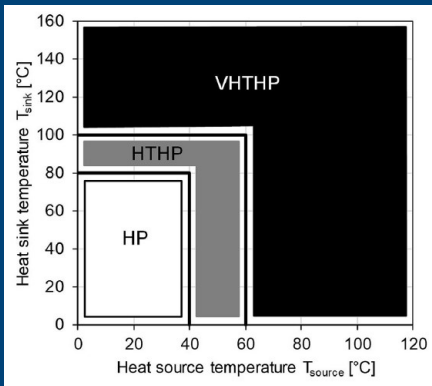


Matching Heat Pumps to Heating & Cooling Profiles in the NZ Food Processing Sector

Don Cleland

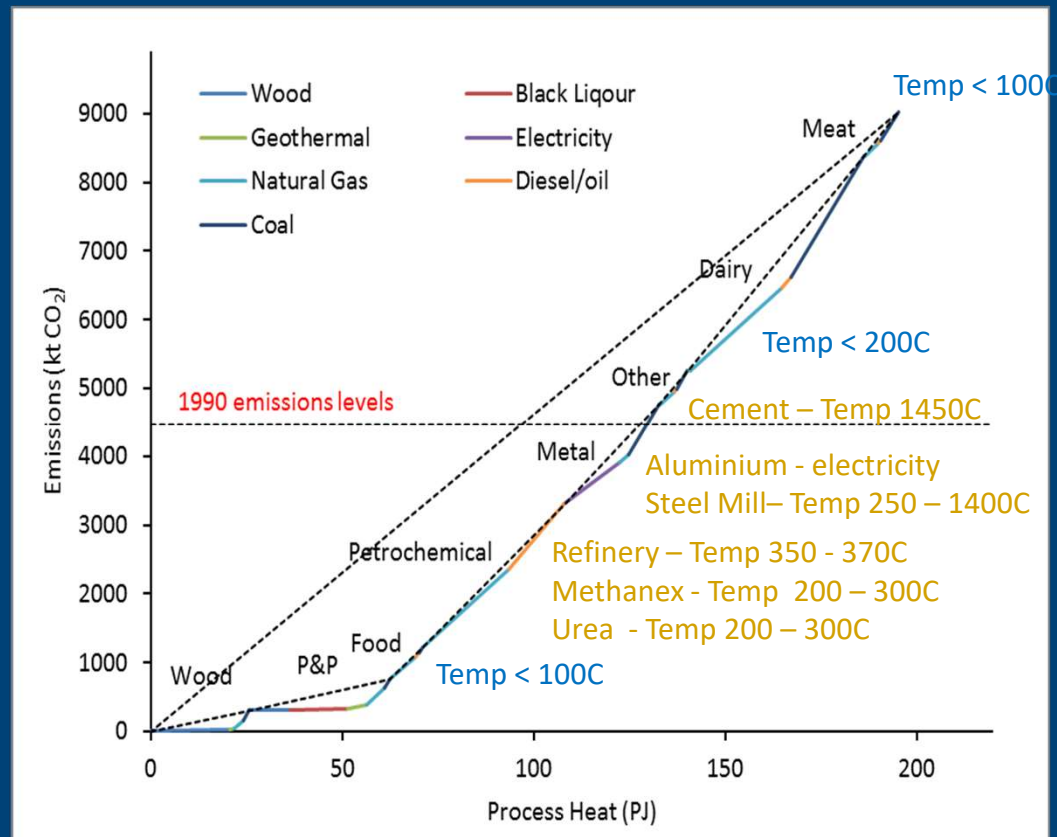
School of Food & Advanced Technology
Massey University
Ahuora Research Programme

28 October 2021



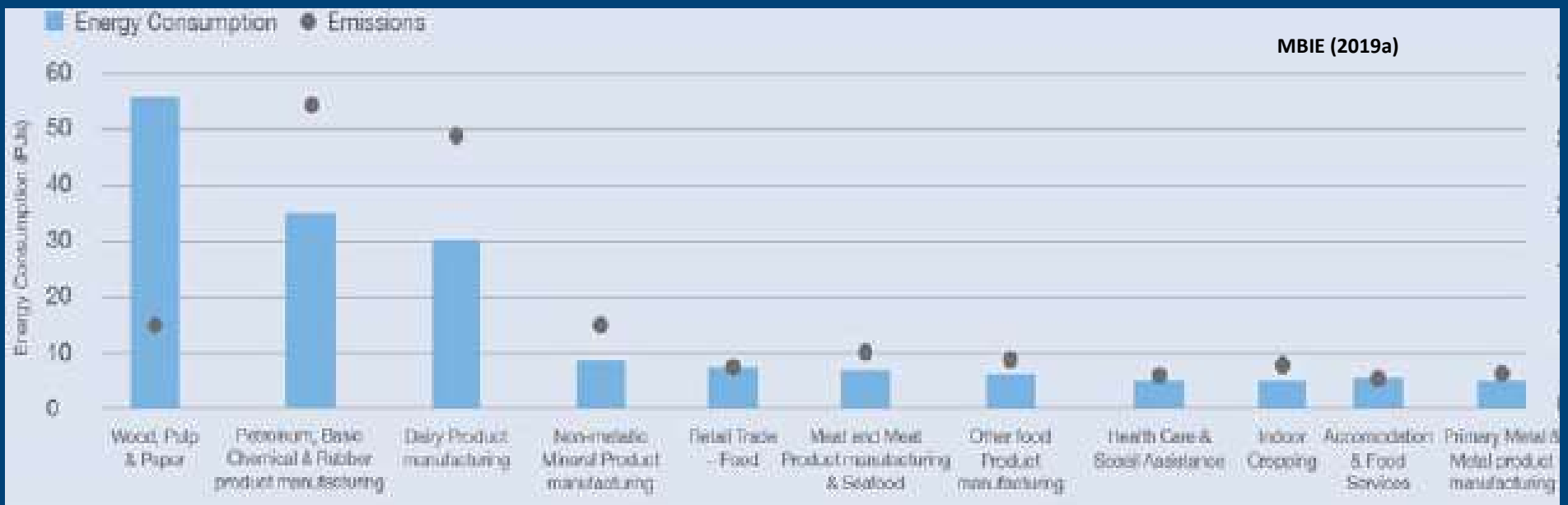
Process Heating in NZ

- 34% NZ energy consumption
- 27% NZ energy-related GHG emissions (2nd behind transport)
- ~ 60% is supplied by burning fossil fuels; mainly in boiler systems
- Also:
 - domestic hot water = ~4% NZ energy
 - space heating of commercial & public building via hot water = ~5% NZ energy



Food Industry Process Heating

- ~25% of NZ process heating across ~200 sites (Atkins, 2019)
- most at temperatures less than 200°C
 - < 100°C – hot water, cleaning, blanching, pasteurization, concentration
 - 100-150°C – sterilisation, cooking, drying
 - >150°C – cooking, drying
- decarbonising options
 - demand reductions
 - electro-technologies e.g. microwave, ohmic, PEF, UV etc
 - heat recovery by heat exchange (HX)
 - heat pumps (HPs)



HP Feasibility Criteria

- Economic

$$\text{COP} > \frac{\text{cost of electricity}}{\text{cost of fuel}} \times \eta_{\text{fuel to useful heat}}$$

- Environmental (e.g. CO₂)

$$\text{COP} > \frac{EF_{\text{electricity}}}{EF_{\text{fuel for heat}}} \times \eta_{\text{fuel to useful heat}}$$

- EF = emissions factor (kt CO_{2eq}/PJ; g CO_{2eq}/MJ)
- need to include production, transmission, distribution & standing losses
- extra capital vs savings in energy costs and emissions

Examples of Use of HP Criteria

- natural gas boiler vs electrical HP in NZ
 - electricity @ \$0.12/kWh
 - gas @ \$11/GJ (\$0.04/kWh)
 - $\eta_{\text{gas to heat}} = 80\%$ (non-condensing boiler)
- economic criteria

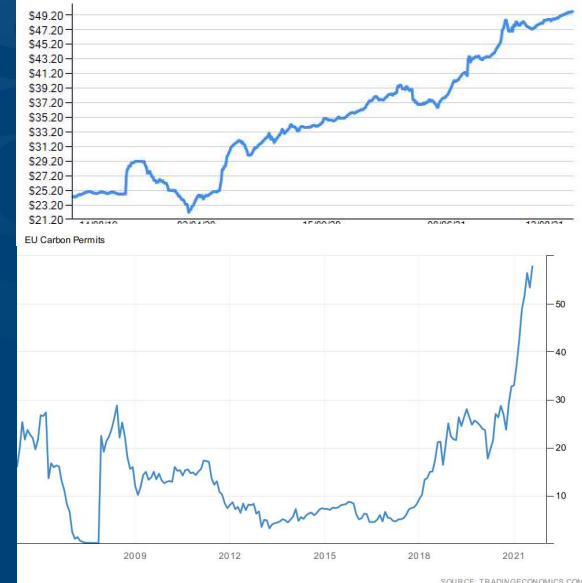
$$\text{COP} > \frac{\text{cost of electricity} \times \eta_{\text{fuel to useful heat}}}{\text{cost of fuel}} = \frac{0.12}{0.04} \times 0.8 = 2.4$$

- environmental (carbon)

$$\text{COP} > \frac{EF_{\text{electricity}}}{EF_{\text{fuel for heat}}} \times \eta_{\text{fuel to useful heat}} = \frac{30}{54} \times 0.8 = 0.4 \quad (\approx 3.5 \text{ in Oz})$$

and even if marginal electricity is CCGT
($\eta_{\text{gas to electricity}} = 50\%$)

$$\text{COP} > \frac{54}{54} \times \frac{0.8}{0.5} = 1.6$$

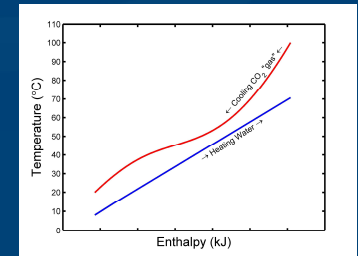


Fuel	Emission Factor
Natural Gas	54 g CO _{2eq} /MJ
LPG	60 g CO _{2eq} /MJ
Coal – bituminous	89 g CO _{2eq} /MJ
Coal – sub-bituminous	92 g CO _{2eq} /MJ
Coal – lignite	93 g CO _{2eq} /MJ
Electricity (2018)	30 g CO _{2eq} /MJ
Electricity (2016)	108 g/kWh
Electricity (2014)	127 g/kWh

HP Potential

- Carnot Efficiency (excluding HX, fans and pumps)
- 50% of COP_{Carnot} realistic if include HX, fans & inefficiencies
- Use log-mean absolute temperatures if glides in sink or source temperatures

$$COP_{carnot} = \frac{T_{hot} + 273}{T_{hot} - T_{cold}}$$



Examples:

- ambient source to 95°C water
- $T_{cold} = 20^{\circ}C$, $T_{hot} = 95^{\circ}C$

$$COP_{carnot} = \frac{95 + 273}{95 - 20} = 4.9 \quad (9.1 \text{ if transcritical})$$

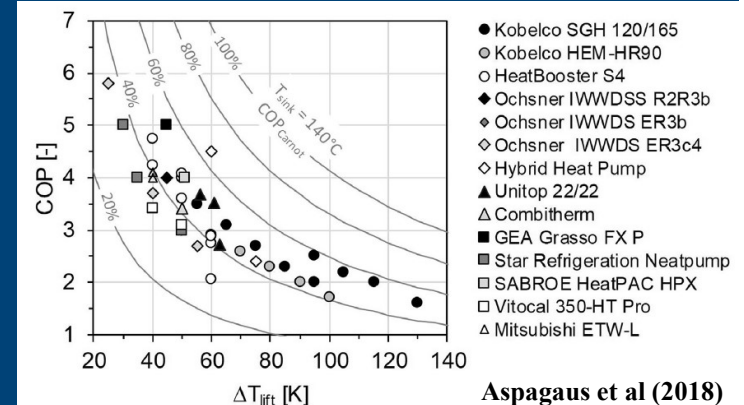
- waste heat source to 60°C water
- $T_{cold} = 30^{\circ}C$, $T_{hot} = 60^{\circ}C$

$$COP_{carnot} = \frac{60 + 273}{60 - 30} = 11.1$$

$$COP_{carnot} = \frac{75 + 273}{75 - 65} = 34.8$$

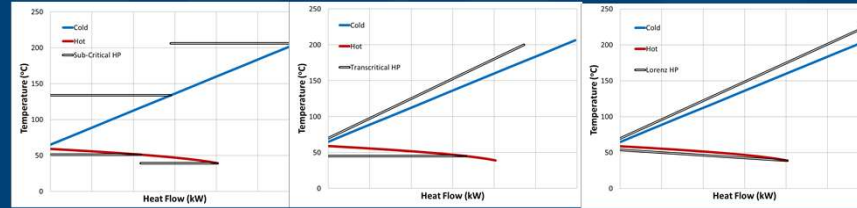
- evaporator MVR – evaporated water at 65°C; steam at 75°C
- $T_{cold} = 65^{\circ}C$, $T_{hot} = 75^{\circ}C$

- Temperature lifts $< \approx 60^{\circ}C$ for $COP_{actual} > 3$
- Need good temperature matching to get high COP



Aspagaus et al (2018)

Case Study Analysis Methodology



- Pinch technology methods used to develop GCCs for typical sites
- Process to process heat recovery given priority over HPs
- HP placed across the pinch
 - below 20°C use refrigeration rejecting @ 25°C to HP or to ambient @ 15°C or a HP
 - HP cycle chosen to match heat sources and sinks (e.g. sub-critical if near constant temp; trans-critical or hybrid absorption-compression if across temp ranges)
 - refrigerants to match temp range (standard equipment pressure, high efficiency)
 - max T_e and min T_c yet fit GCC
 - size HP to maximise limiting heat flow (cooling or heating) i.e. all cooling & heating useful
 - multi-staging or cascades if $PR > 6$ (> 1.5 for R718)
 - ambient if HP waste sources limiting
 - residual heating & cooling using traditional boilers or refrigeration

Options and Assumptions

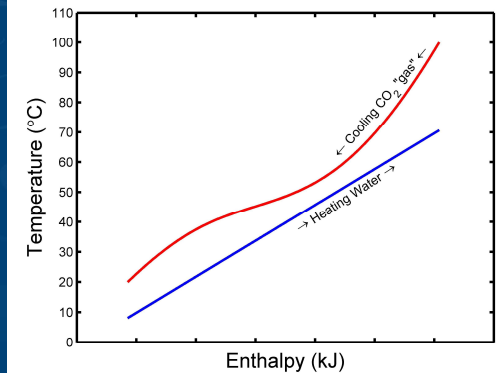
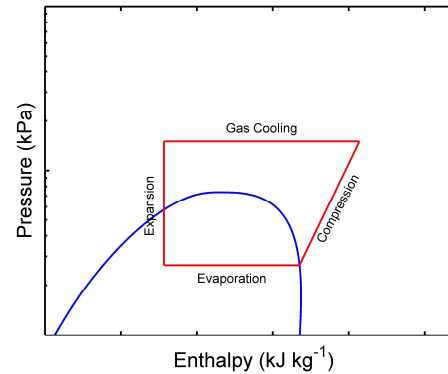
- Refrigerants & Cycles

- R717 up to 60 bar
- R744 up to 150 bar with IHX
- multi-stage R718 above 70°C
- hybrid absorption-compression R717-R718
- other refrigerants if better matches e.g. R600, R134a, R245fa, R1336mzz(Z), R1234ze(E)

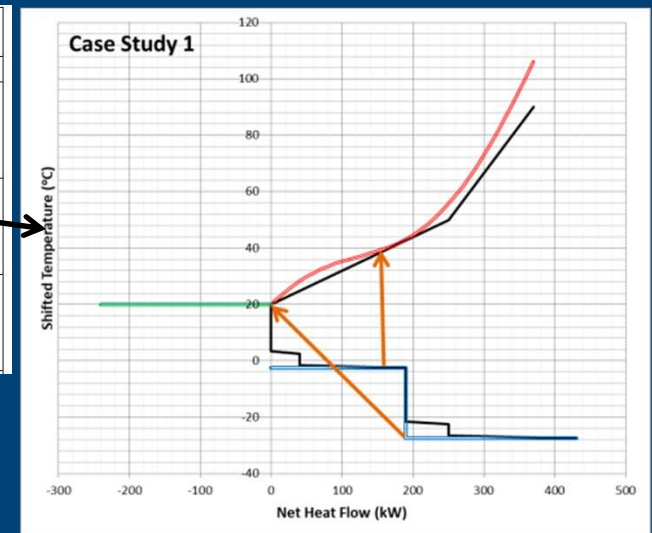
- Technical & Economic Data

- 75% isentropic efficiency for compressor, pumps, turbines
- negligible heat losses, pressure drops, SH and SC
- energy for ambient cooling @ 3% of heat of rejection
- HP or refrigeration capital = \$NZ1000/kW
- electricity @ \$0.12/kWh; EF=30 kg CO₂/GJ
- fuel @ \$0.04/kWh; $\eta_{\text{boiler}}=85\%$; EF=54 kg CO₂/GJ
- carbon @ \$25/tonne CO_{2eq}
- 250 days operation per year

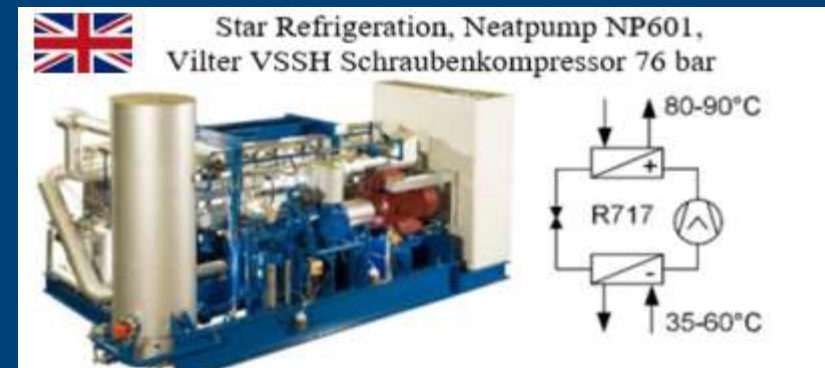
Case Study - Meat Processing Without Rendering



Hot & Cold Utility Options	Placement	COP _h or COP _r	Electricity Use (kW)	Fuel Use (kW)	Energy Cost (\$/h)	CO ₂ Emissions (kg/h; \$/h)
Case Study 1 – Meat processing without rendering						
Boiler	370 kW _i @ 100°C	-	0	435.3	\$17.41	84.6; \$2.12
R717 Refrig.	240+190 kW _r @ -30/-5/25°C (10.0 bar)	3.72	115.4	-	\$13.85	12.5; \$0.31
Ambient	546 kW _e @ 15°C	-	16.4	-	\$1.97	1.8; \$0.04
			131.8		\$33.23	98.8; \$2.48
R744 HP	71+190 kW _i +370 kW _h @ -30/-5°C/93.5 bar	5.80	108.8	-	\$13.06	11.8; \$0.29
R744 Refrig.	169+0 kW _r @ -30/-5/25°C (64.3 bar)	2.36	71.5*	-	\$ 8.58	7.7; \$0.19
Ambient	240 kW _e @ 15°C	-	7.2	*58.9kW _e (if R717)	\$ 0.86	0.8; \$0.02
			187.5		\$22.50	20.3; \$0.51
R717 HP	250+120 kW _h @ 25/51/89°C (50.1 bar)	6.92	53.5	-	\$ 6.42	5.8; \$0.14
R717 Refrig.	240+190 kW _r @ -30/-5/25°C (10.0 bar)	3.72	115.4	-	\$13.85	12.5; \$0.31
Ambient	229 kW _e @ 15°C	-	6.9	-	\$ 0.83	0.7; \$0.02
			175.8		\$21.10	19.0; \$0.47

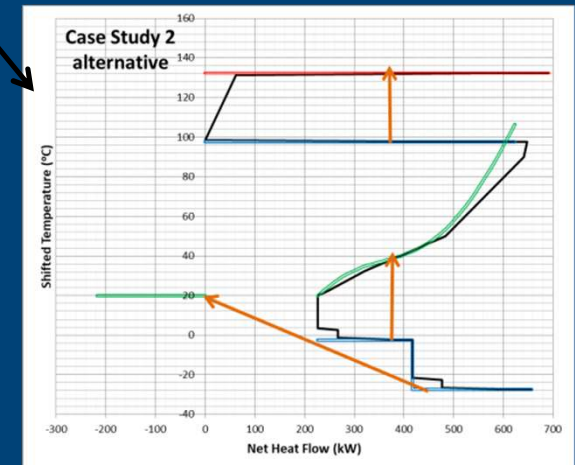
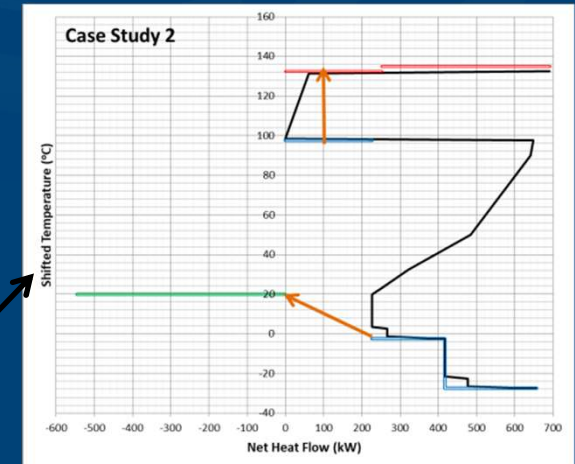


- Heating limited so residual refrig to ambient
- Trans-critical R744 (refrig+heating)
 - saves \$12.70/h over boiler +R717 refrig
 - \$109k higher capital (1.4 year payback)
- R717 Refrig + R717 or R134a HP
 - saves \$14.40/h over boiler + R717 refrig
 - \$307k higher capital (3.6 year payback)



Case Study - Meat Processing With Rendering

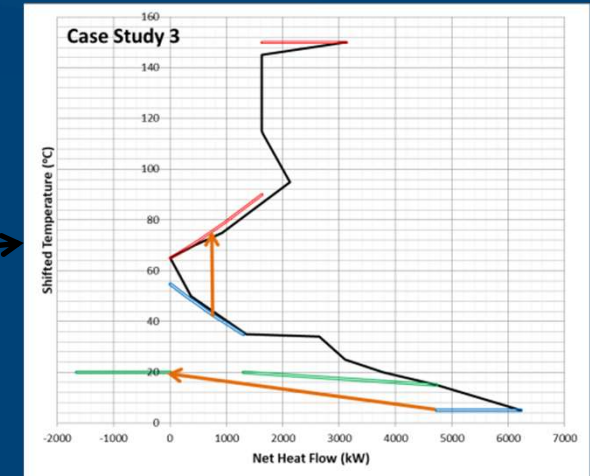
Hot & Cold Utility Options	Placement	COP _h or COP _r	Electricity Use (kW)	Fuel Use (kW)	Energy Cost (\$/h)	CO ₂ Emissions (kg/h; \$/h)
Boiler	692 kW _t @ 135°C	-	0	814.1	\$32.56	158.3; \$3.96
R717 Refrig.	240+190 kW _r @ -30/-5/25°C (10.0 bar)	3.72	115.4	-	\$13.85	12.5; \$0.31
Ambient	227 kW _c + 545 kW _c @ 15°C	-	23.2	-	\$ 2.78	2.5; \$0.06
			138.6		\$49.19	173.3; \$8.29
Boiler	440 kW _t @ 135°C	-	-	517.6	\$20.70	100.6; \$2.52
R718 HP (open)	227 kW _c + 252 kW _h @ 100/130°C (3 stage)	9.97	25.3	-	\$3.04	2.7; \$0.07
R717 Refrig.	240+190 kW _r @ -30/-5/25°C (10.0 bar)	3.72	115.4	-	\$13.85	12.5; \$0.31
Ambient	546 kW _c @ 15°C	-	16.4	-	\$1.97	1.8; \$0.09
			157.1		\$39.56	117.6; \$2.99
R718 HP (open)	623 kW _c +692 kW _h @ 100/130°C (3 stage)	9.97	69.5	-	\$8.34	7.5; \$0.19
R744 HP	87+190 kW _r +397 kW _h @ -30/-5/96.1 bar	3.66	184.2	-	\$22.10	19.9; \$0.50
R744 Refrig.	153+0 kW _r @ -30/-5/25°C (64.3 bar)	2.36	64.7*	*53.3kW _e	\$7.76	7.0; \$0.17
Ambient	218 kW _c @ 15°C	-	6.5	(if R717)	\$0.78	0.7; \$0.02
			324.9		\$38.99	35.1; \$0.88
R718 HP	227 kW _c + 261 kW _h @ 95/135°C (4 stage)	7.60	34.3		\$4.12	3.7; \$0.09
R718 HP+	353 kW _c + 431 kW _h @ 80/135°C (5 stage)	5.55	77.6		\$9.31	8.4; \$0.21
+R717 HP	260 kW _c + 353 kW _h @ 25/51/85°C (46.1 bar)	3.77	93.6	-	\$11.23	10.1; \$0.25
R717 Refrig.	240+190 kW _r @ -30/-5/25°C (10.0 bar)	3.72	115.4		\$13.85	12.5; \$0.31
Ambient	286 kW _c @ 15°C	-	8.6		\$1.03	0.9; \$0.05
			329.5		\$39.54	35.6; \$1.78
Boiler	415 kW _t @ 135°C	-	-	488.2	\$19.53	94.9; \$2.37
R1336mzz(Z) HP	227 kW _c + 277 kW _h @ 95/135°C (14.9 bar)	5.50	50.3	-	\$6.04	5.4; \$0.14
R717 Refrig.	240+190 kW _r @ -30/-5/30°C	3.72	115.4	-	\$13.85	12.5; \$0.31
Ambient	546 kW _c @ 15°C	-	16.4	-	\$1.97	1.8; \$0.09
			182.1		\$41.39	114.6; \$2.87



- R718 HP+R717 refrig (or R718 HP+R744 HP/Refrig)
 - saves \$14.90/h (\$17.61/h) over boiler+R717 refrig
 - \$252k (\$812k) higher capital so 2.8 year (7.7 year) payback

Case Study - General Food Processing

Hot & Cold Utility Options	Placement	COP _h or COP _r	Electricity Use (kW)	Fuel Use (kW)	Energy Cost (\$/h)	CO ₂ Emissions (kg/h; \$/h)
Boiler+Cogen R717 Refrig. Ambient	1625+1500 kW _t @ 87/150°C	-	-203.0	3915	\$132.24	739.2; \$18.48
	1500 kW _r @ 5/25°C	9.59	156.4	-	\$18.77	16.9; \$0.42
	4725 + 1656 kW _c @ 15°C	-	191.4	-	\$22.97	20.7; \$0.52
			144.8	-	\$173.98	776.7; \$19.42
Boiler Hybrid HP (x=0.5) R717 Refrig. Ambient	1500 kW _t @ 150°C	-	0	1765	\$70.60	343.1; \$8.58
	1299 kW _c @ 2.92 bar; 31-51°C+	4.98	326.2	-	\$39.14	35.2; \$0.88
	+1625 kW _h @ 11.7 bar; 70-95°C	-	-	-	-	-
	1500 kW _r @ 5/25°C	9.59	156.4	-	\$18.77	16.9; \$0.42
Boiler R717 HP R717 HP R717 Refrig. Ambient	3426 kW _c + 1656 kW _c @ 15°C	-	152.5	-	\$18.30	16.5; \$0.41
			635.1	-	\$146.81	411.7; \$10.29
	1500 kW _t @ 150°C	-	0	1765	\$70.60	343.1; \$8.58
	700 kW _c +906 kW _h @ 40/92°C (53 bar)	4.39	206.2	-	\$24.74	22.3; \$0.56
Boiler R717 HP R717 HP R717 Refrig. Ambient	567 kW _c +719 kW _h @ 32/80°C (41 bar)	4.72	152.2	-	\$18.26	16.4; \$0.41
	1500 kW _r @ 5/25°C	9.59	156.4	-	\$18.77	16.9; \$0.42
	3458 kW _c + 1656 kW _c @ 15°C	-	153.4	-	\$18.41	16.6; \$0.41
			668.2	-	\$150.78	415.3; \$10.38



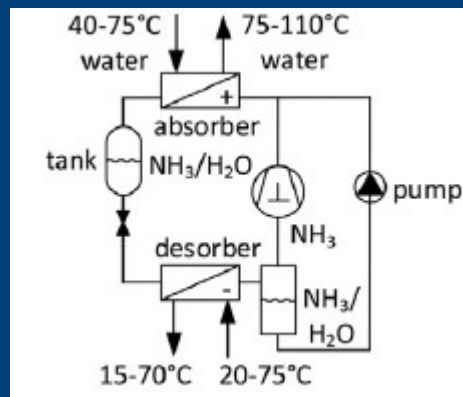
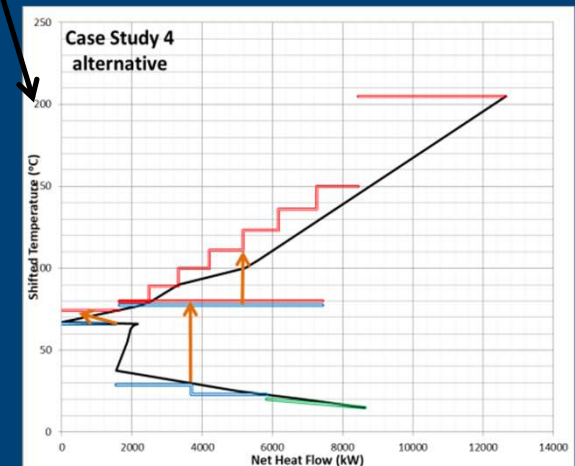
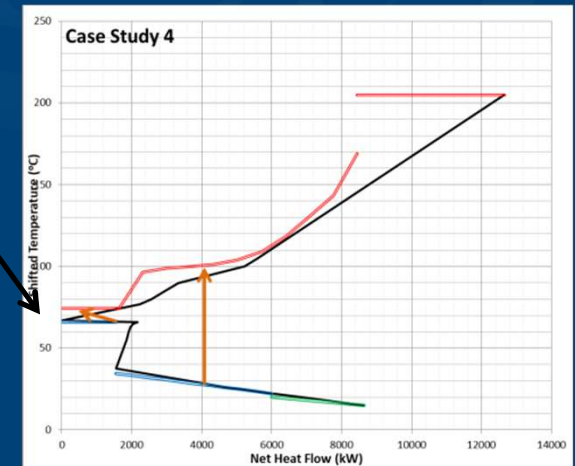
- Hybrid R717+R718 HP best match for heating & cooling near pinch (COP=5)
 - saves \$36.30/h over boiler+cogen+R717 refrig
 - \$1,652k higher capital so 7.6 year payback
- HP heating at 150°C not economic as residual heat source <32°C (e.g. R717+R718 cascade has COP=2.4)



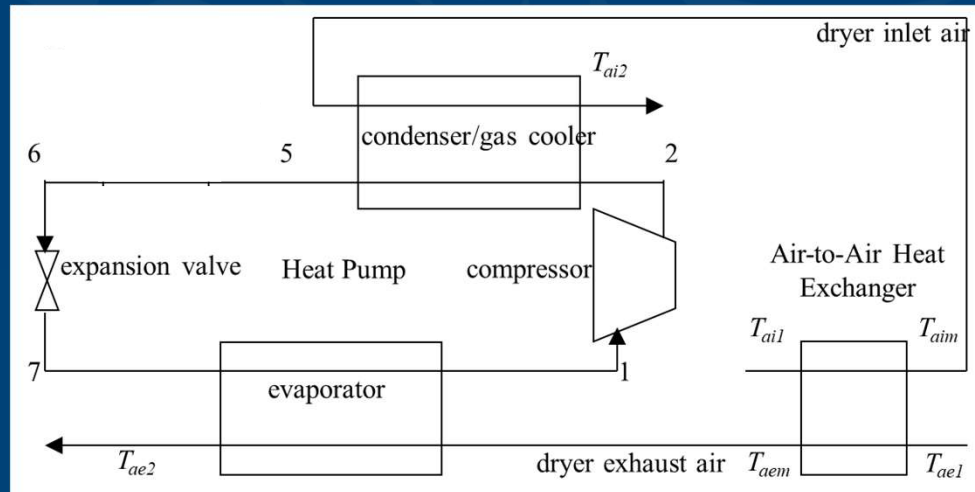
Case Study - Dairy Powder Processing

Hot & Cold Utility Options	Placement	COP _h or COP _t	Electricity Use (kW)	Fuel Use (kW)	Energy Cost (\$/h)	CO ₂ Emissions (kg/h; \$/h)
Boiler+Cogen Ambient	4274+4050+4329 kW _t @ 100/150/205°C 8640 kW _c @ 15°C	-	-1235 259.2 -975.8	16339 -	\$505.36 \$31.10 \$536.46	3043; \$76.07 28.0; \$0.70 3071; \$76.77
Boiler R718 HP	4217 kW _t @ 205°C	-	0	4961	\$198.44	964.4; \$24.11
Hybrid HP	1550 kW _c + 1634 kW _h @ 66/79.3°C (2 stage)	19.6	83.6	-	\$10.03	9.0; \$0.23
(x=0.95)	4447 kW _c @ 7.5 bar; 17.8-34.6°C	2.89	2359	-	\$283.08	254.8; \$6.37
Ambient	6805 kW _h @ 63 bar; 79-174°C	-	-	-	-	-
	2643 kW _c @ 15°C	-	79.3	-	\$9.52	8.6; \$0.21
			2521.9		\$501.07	1237; \$30.92
Boiler R718 HP	4217 kW _t @ 205°C	-	0	4961	\$198.44	964.4; \$24.11
R718 HP+	1550 kW _c + 1634 kW _h @ 66/79.3°C (2 stage)	19.6	83.6	-	\$10.03	9.0; \$0.23
+R717 HP	5797 kW _c + 6805 kW _h @ 80/160°C (7 stage)	6.75	1008	-	\$120.96	108.9; \$2.72
Ambient	2140+2140 kW _c +5797 kW _h @ 18/24/85°C	3.82	1518	-	\$182.16	163.9; \$4.10
	2810 kW _c @ 15°C	-	84.3	-	\$10.12	9.1; \$0.23
			2693.9		\$521.71	1255; \$31.38

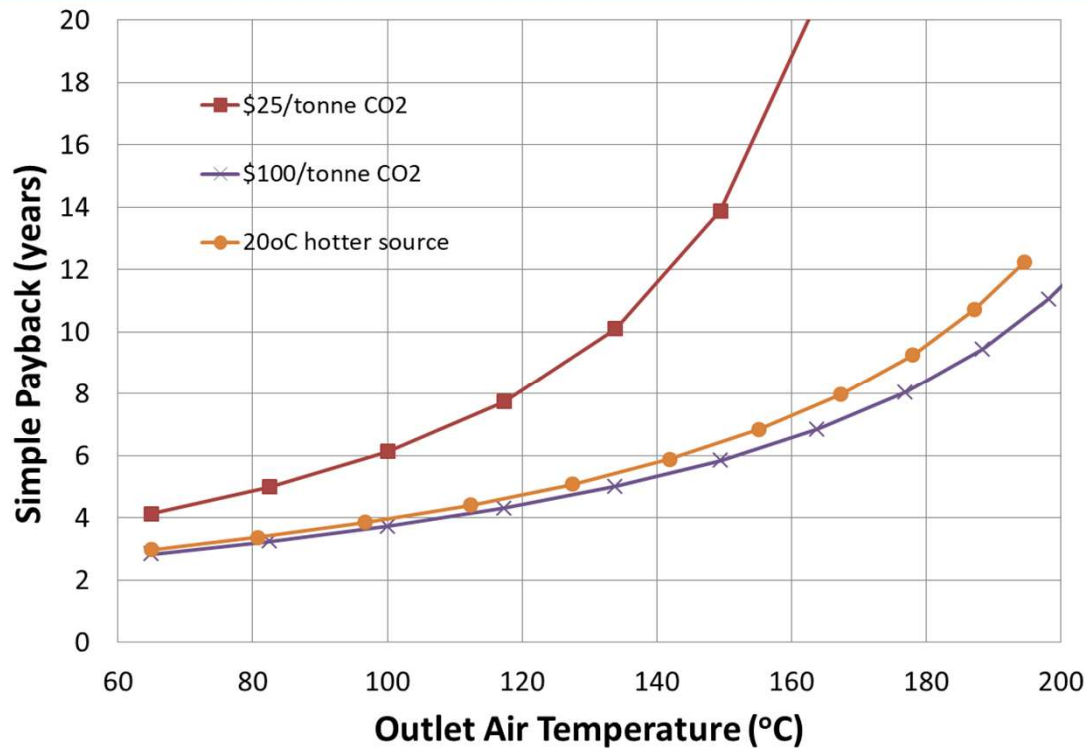
- R718 HP near pinch is cost-effective (COP=19.6)
- For heating up to 150°C
 - Hybrid R717+R718 HP has COP=2.9 but high pressure
 - R717+R718 cascade (9 stages) has COP=2.7 but complex
 - > \$150/tonne CO_{2eq} required to get payback < 5 years



HP Feasibility - Spray Drying

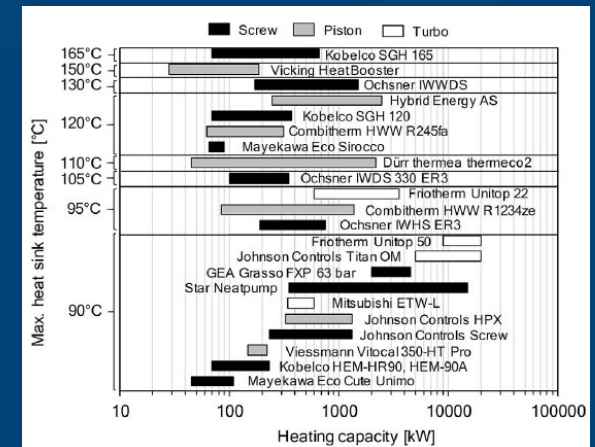


- heating air from 65°C
- using exhaust air as heat source
- electricity @ \$0.12/kWh
- gas @ \$11/GJ (\$0.04/kWh)
- $\eta_{\text{boiler}} = 80\%$
- COP = 50% of Carnot
- capital cost @ \$1000/kW

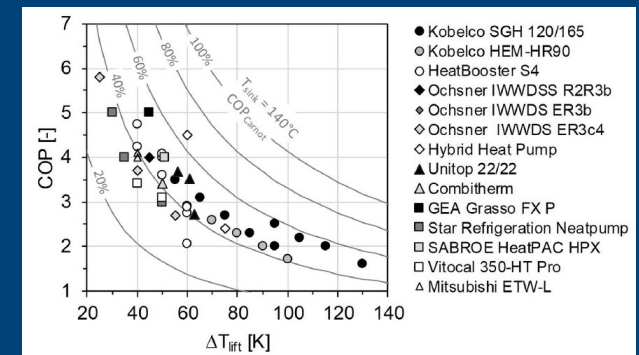


Conclusions

- High potential for existing HP technology $< \sim 130^\circ\text{C}$
- Electrical upgrade can be an extra constraint
- HPs marginal for residual heating common in NZ after heat recovery because
 - sinks $> 120^\circ\text{C}$
 - sources at or just above ambient
- Matching temperature profiles help get higher COPs
- Thermodynamic limits mean usually $\text{COP} < 3$
- Need $> \$150/\text{tonne CO}_{2\text{eq}}$ for HTHP to be feasible
- NZ lacks experience with HTHPs
- Other low carbon process heating sources are also highly constrained



Aspagaus et al (2018)



Questions



Professor Don J. Cleland
Email: d.cleland@massey.ac.nz