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

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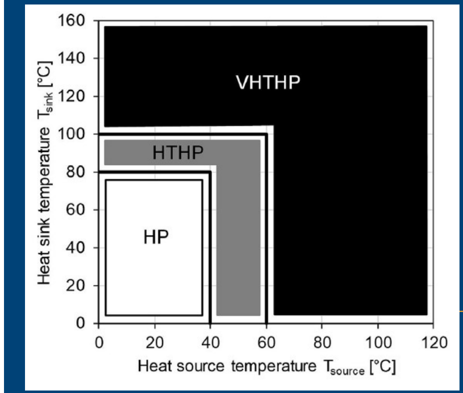
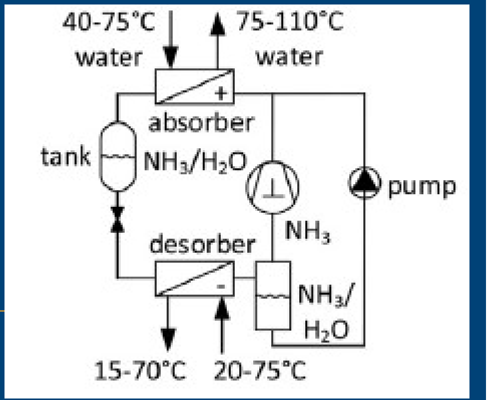
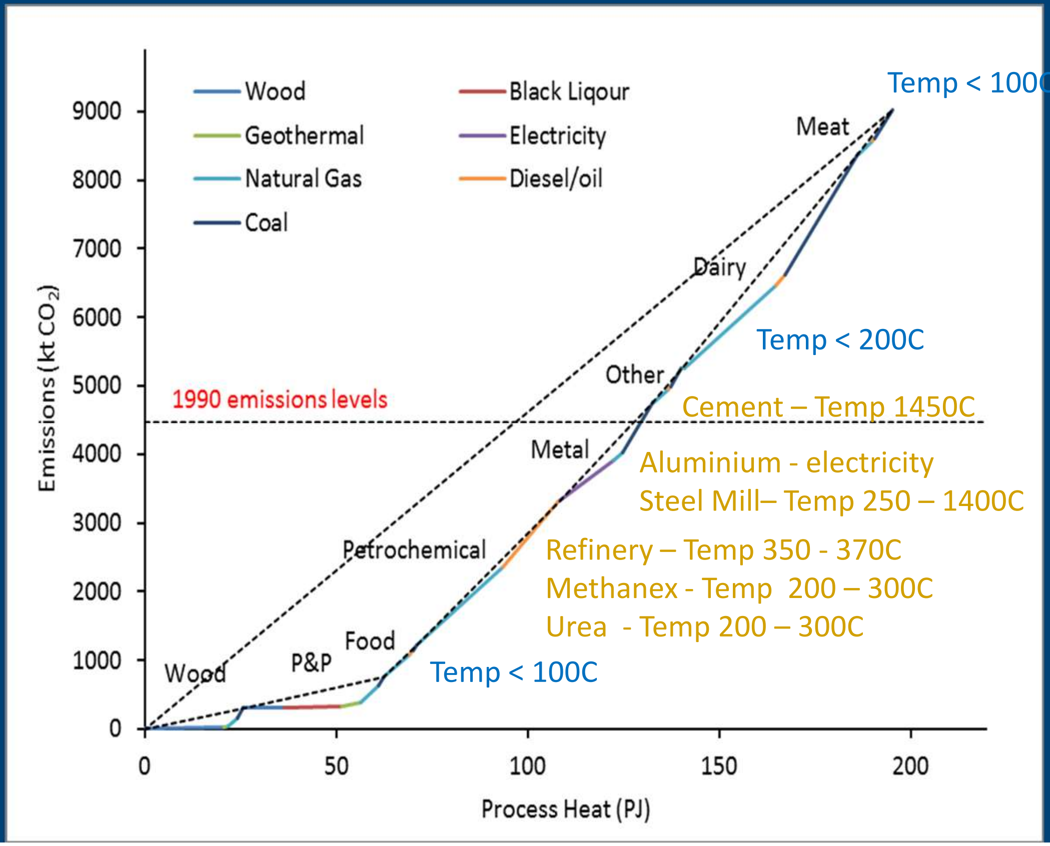




Process Heating in NZ

- 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
  - spacing heating of commercial & public building via hot water = ~5% NZ energy



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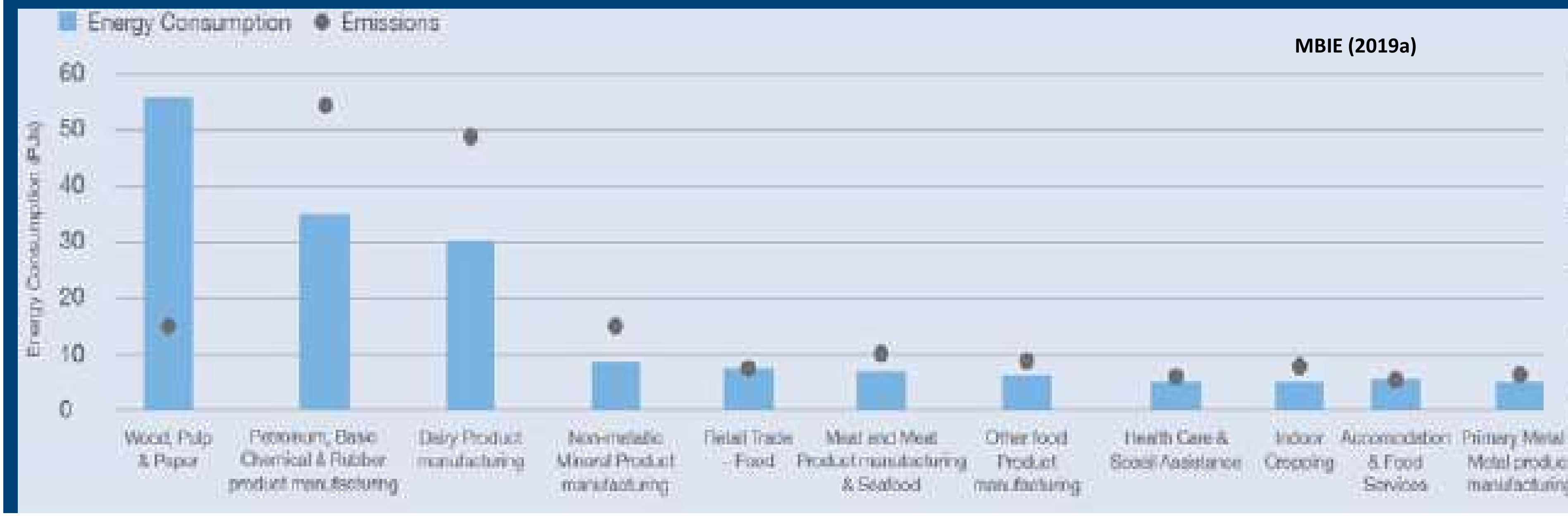
Food Industry Process Heating

- ~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)



MBIE (2019a)

HP Feasibility Criteria

- Economic

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

- Environmental (e.g. CO_2)

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

- *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

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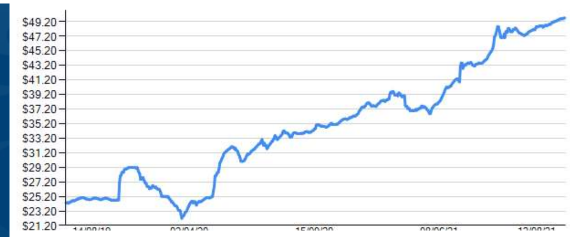
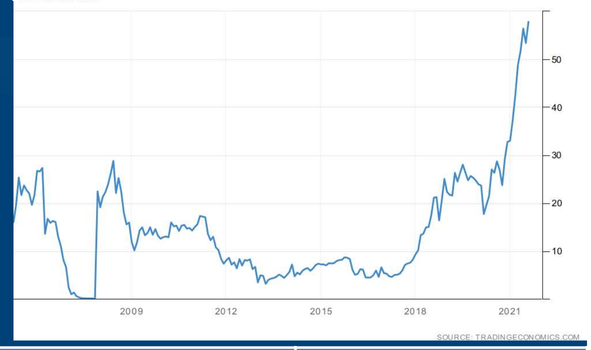
Examples of Use of HP Criteria



EU Carbon Permits



- 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 ($\eta_{\text{gas to electricity}} = 50\%$)

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

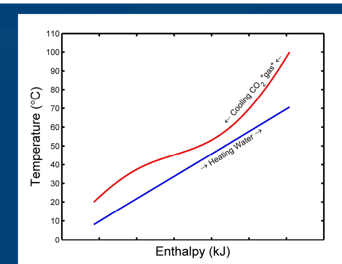
Fuel	Emission Factor
Natural Gas	54 g CO_{2eq}/MJ
LPG	60 g CO_{2eq}/MJ
Coal – bituminous	89 g CO_{2eq}/MJ
Coal – sub-bituminous	92 g CO_{2eq}/MJ
Coal – lignite	93 g CO_{2eq}/MJ
Electricity (2018)	30 g CO_{2eq}/MJ 108 g/kWh
Electricity (2016)	98 g/kWh
Electricity (2014)	127 g/kWh

MBIE (2019b)

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°C, T_{hot} = 95°C

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

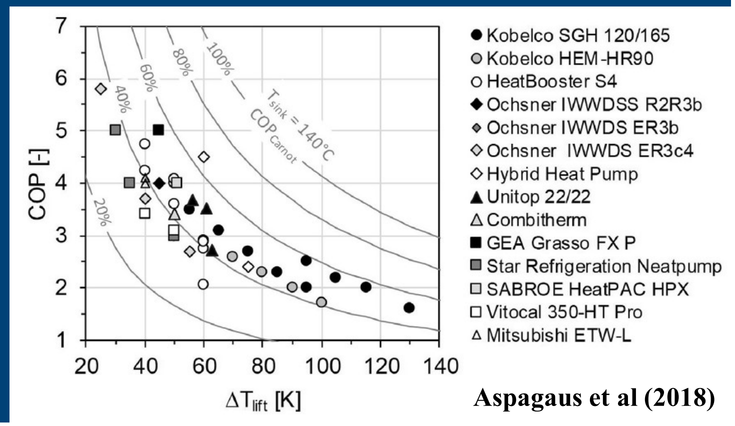
  - waste heat source to 60°C water
  - T_{cold} = 30°C, T_{hot} = 60°C

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

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

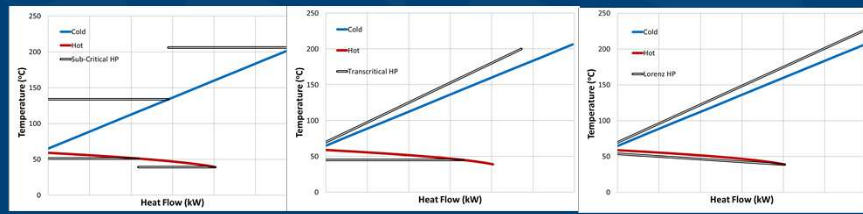
$$COP_{carnot} = \frac{75 + 273}{75 - 65} = 34.8$$

- Temperature lifts < ≈60°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

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Options and Assumptions

- Refrigerants & Cycles
  - R717 up to 60 bar
  - R744 up to 150 bar with IHX
  - multi-stage R718 above 70^{o}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 CO_2/GJ
  - fuel @ $0.04/kWh; η_{boiler}=85%; EF=54 kg CO_2/GJ
  - carbon @ $25/tonne CO_{2eq}
  - 250 days operation per year

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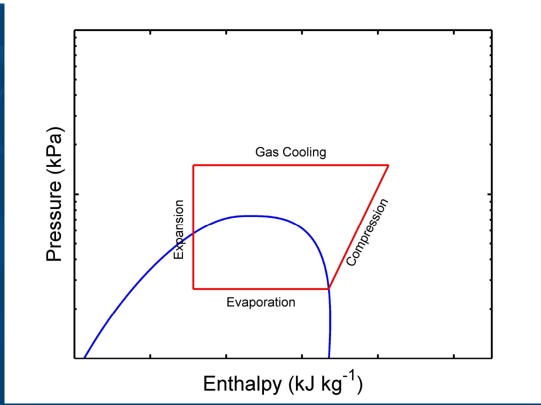
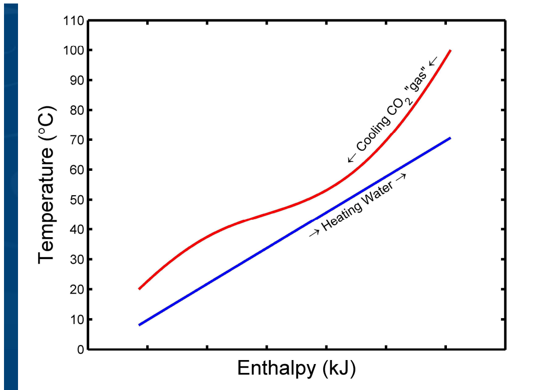
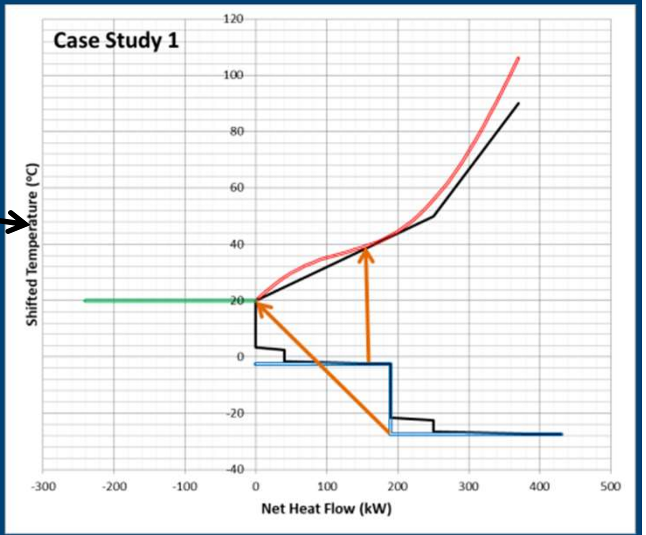
Case Study - Meat Processing Without Rendering

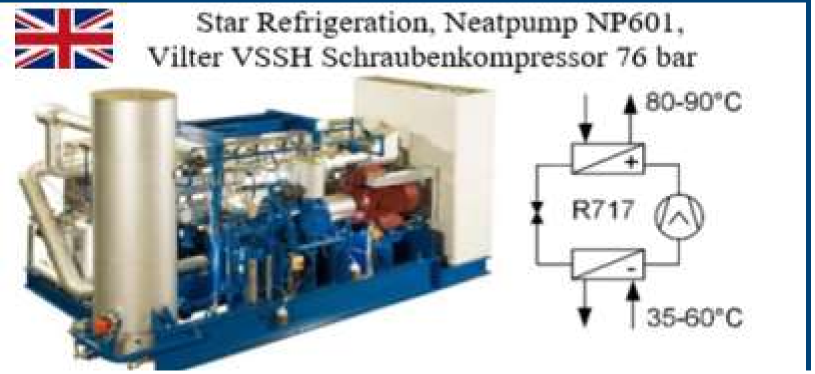




Hot & Cold Utility Options	Placement	COP_h or COP_r	Electricity Use (kW)	Fuel Use (kW)	Energy Cost ($/h)	CO_2 Emissions (kg/h; $/h)
Case Study 1 – Meat processing without rendering						
Boiler R717 Refrig. Ambient	370 kW_t @ 100°C 240+190 kW_r @ -30/-5/25°C (10.0 bar) 546 kW_c @ 15°C	- 3.72 -	0 115.4 16.4 131.8	435.3 - -	$17.41 $13.85 $ 1.97 $33.23	84.6; $2.12 12.5; $0.31 1.8; $0.04 98.8; $2.48
R744 HP R744 Refrig. Ambient	71+190 kW_r+370 kW_h @ -30/-5°C/93.5 bar 169+0 kW_r @ -30/-5/25°C (64.3 bar) 240 kW_c @ 15°C	5.80 2.36 -	108.8 71.5* 7.2 187.5	- *58.9kW_e (if R717)	$13.06 $ 8.58 $ 0.86 $22.50	11.8; $0.29 7.7; $0.19 0.8; $0.02 20.3; $0.51
R717 HP R717 Refrig. Ambient	250+120 kW_h @ 25/51/89°C (50.1 bar) 240+190 kW_r @ -30/-5/25°C (10.0 bar) 229 kW_c @ 15°C	6.92 3.72 -	53.5 115.4 6.9 175.8	-	$ 6.42 $13.85 $ 0.83 $21.10	5.8; $0.14 12.5; $0.31 0.7; $0.02 19.0; $0.47

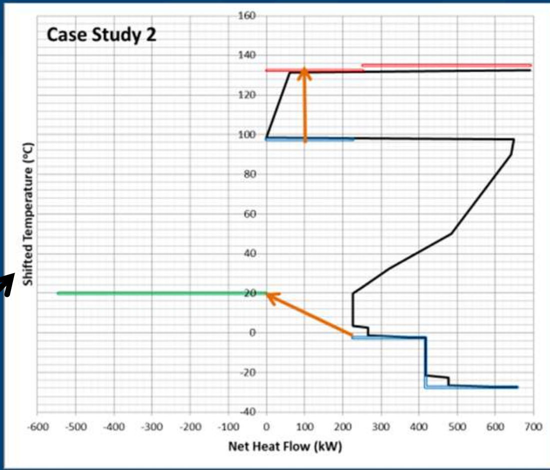


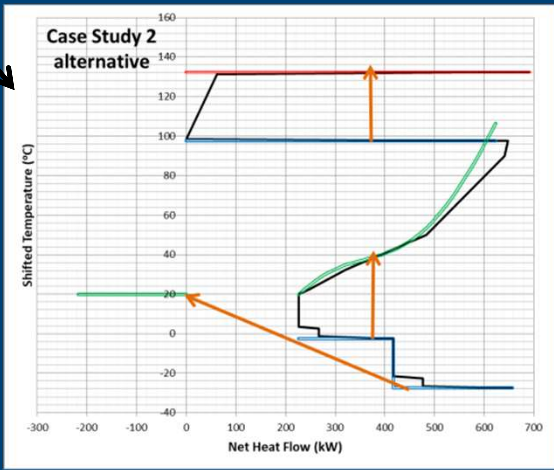
- Heating limited so residual refrig to ambient
- Trans-critical R744 (refrig+heating)
  - saves $12.70/h over boiler +R717 refrig
  - $109k higher capital (1.4 year payback)
- R717 Refrig + R717 or R134a HP
  - saves $14.40/h over boiler + R717 refrig
  - $307k higher capital (3.6 year payback)



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

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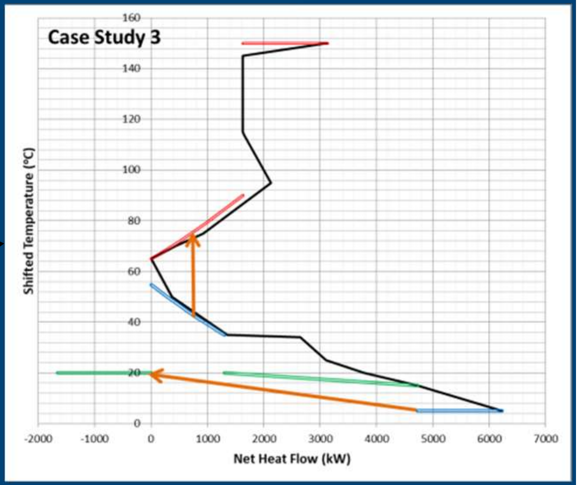
Case Study - General Food Processing

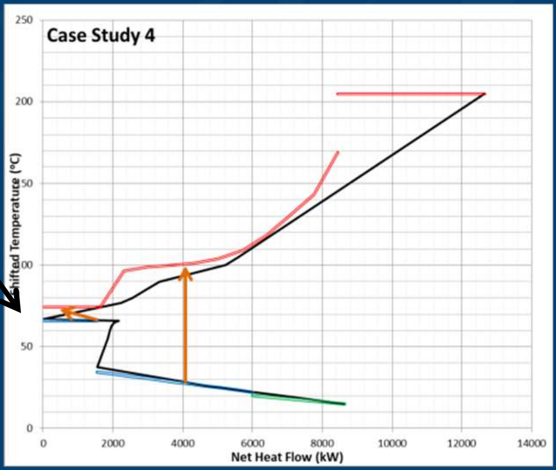
Hot & Cold Utility Options	Placement	COP_h or COP_r	Electricity Use (kW)	Fuel Use (kW)	Energy Cost ($/h)	CO_2 Emissions (kg/h; $/h)
Boiler+Cogen	1625+1500 kW_t @ 87/150°C	-	-203.0	3915	$132.24	739.2;$18.48
R717 Refrig.	1500 kW_r @ 5/25°C	9.59	156.4	-	$18.77	16.9; $0.42
Ambient	4725 + 1656 kW_c @ 15°C		191.4	-	$22.97	20.7; $0.52
			144.8		$173.98	776.7;$19.42
Boiler	1500 kW_t @ 150°C	-	0	1765	$70.60	343.1; $8.58
Hybrid HP (x=0.5)	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	-	-	-	-	-
R717 Refrig.	1500 kW_r @ 5/25°C	9.59	156.4	-	$18.77	16.9; $0.42
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
Boiler	1500 kW_t @ 150°C	-	0	1765	$70.60	343.1; $8.58
R717 HP	700 kW_c+906 kW_h @ 40/92°C (53 bar)	4.39	206.2	-	$24.74	22.3; $0.56
R717 HP	567 kW_c+719 kW_h @ 32/80°C (41 bar)	4.72	152.2	-	$18.26	16.4; $0.41
R717 Refrig.	1500 kW_r @ 5/25°C	9.59	156.4	-	$18.77	16.9; $0.42
Ambient	3458 kW_c + 1656 kW_c @ 15°C	-	153.4	-	$18.41	16.6; $0.41
			668.2		$150.78	415.3;$10.38

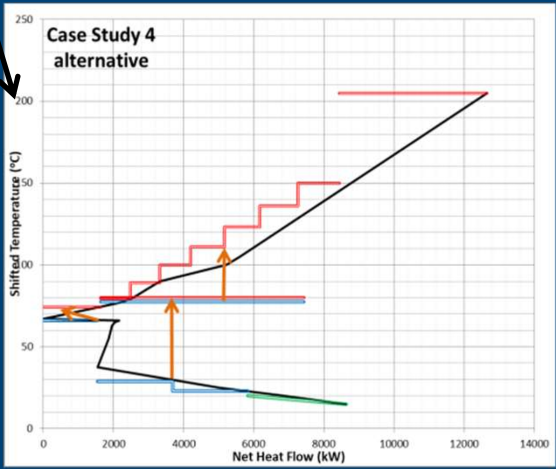


- Hybrid R717+R718 HP best match for heating & cooling near pinch (COP=5)
  - saves $36.30/h over boiler+cogen+R717 refrig
  - $1,652k higher capital so 7.6 year payback
- HP heating at 150°C not economic as residual heat source <32°C (e.g. R717+R718 cascade has COP=2.4)

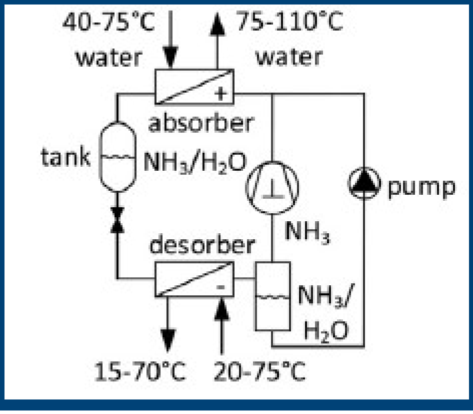
Case Study - Dairy Powder Processing

Hot & Cold Utility Options	Placement	COP_h or COP_r	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 Hybrid HP (x=0.95) Ambient	4217 kW_t @ 205°C 1550 kW_c + 1634 kW_h @ 66/79.3°C (2 stage) 4447 kW_c @ 7.5 bar; 17.8-34.6°C 6805 kW_h @ 63 bar; 79-174°C 2643 kW_c @ 15°C	- 19.6 2.89 - -	0 83.6 2359 - 79.3 2521.9	4961 - - - -	$198.44 $10.03 $283.08 - $9.52 $501.07	964.4;$24.11 9.0; $0.23 254.8; $6.37 - 8.6; $0.21 1237; $30.92
Boiler R718 HP R718 HP+ +R717 HP Ambient	4217 kW_t @ 205°C 1550 kW_c + 1634 kW_h @ 66/79.3°C (2 stage) 5797 kW_c + 6805 kW_h @ 80/160°C (7 stage) 2140+2140 kW_c+5797 kW_h @ 18/24/85°C 2810 kW_c @ 15°C	- 19.6 6.75 3.82 -	0 83.6 1008 1518 84.3 2693.9	4961 - - - -	$198.44 $10.03 $120.96 $182.16 $10.12 $521.71	964.4;$24.11 9.0; $0.23 108.9; $2.72 163.9: $4.10 9.1; $0.23 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



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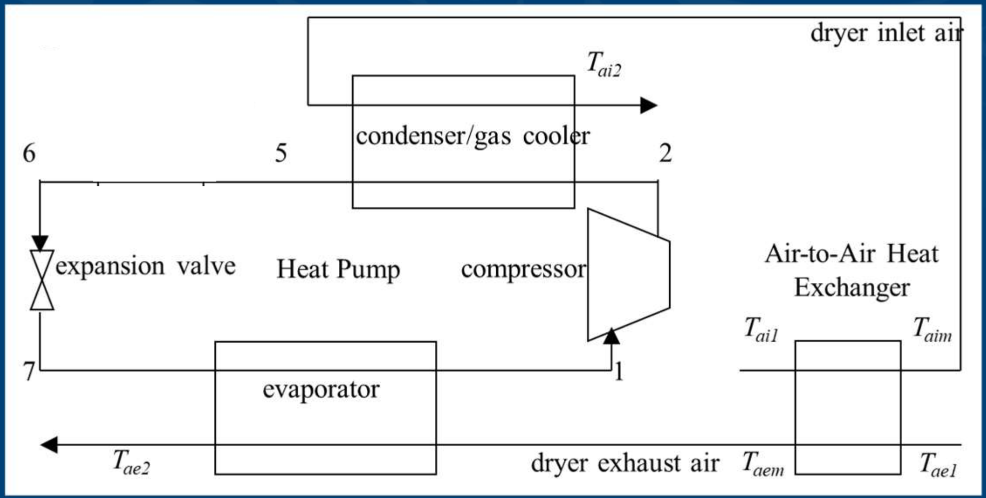
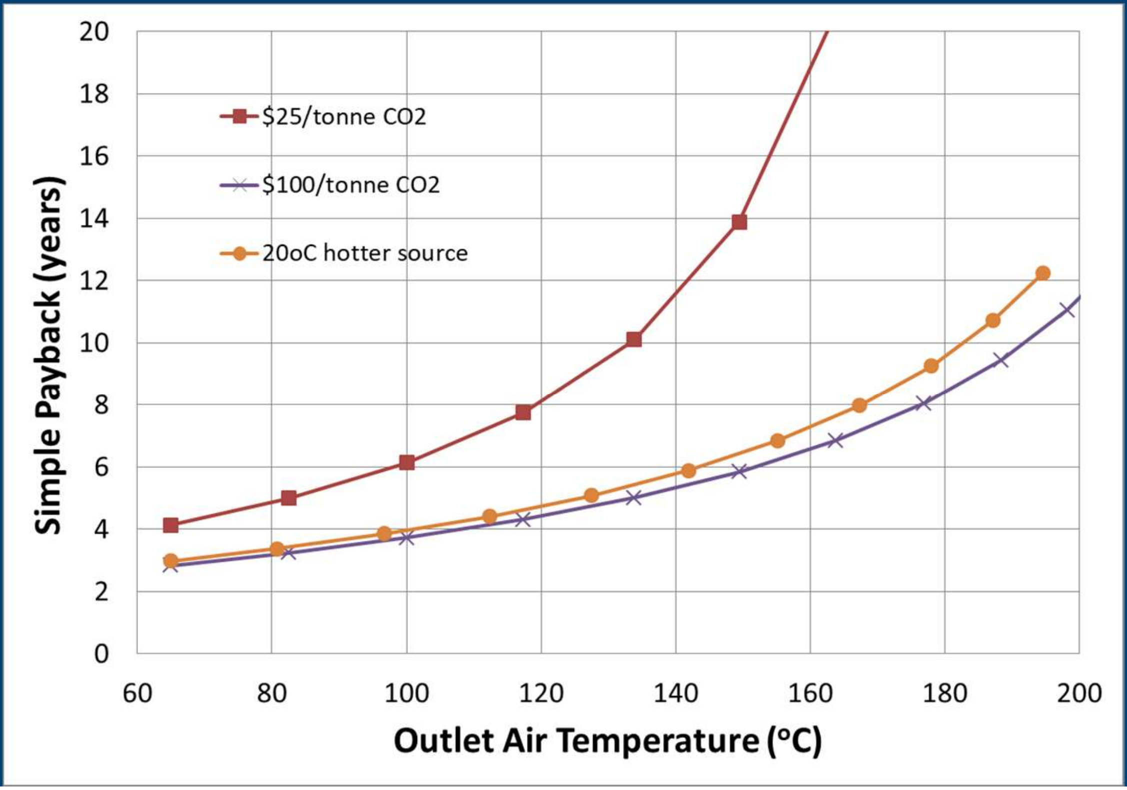
HP Feasibility - Spray Drying



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



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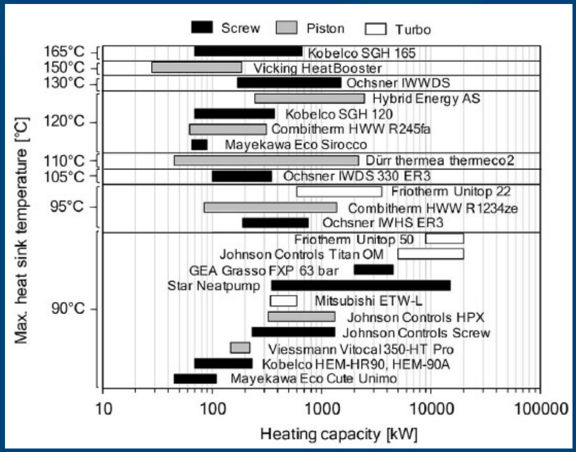
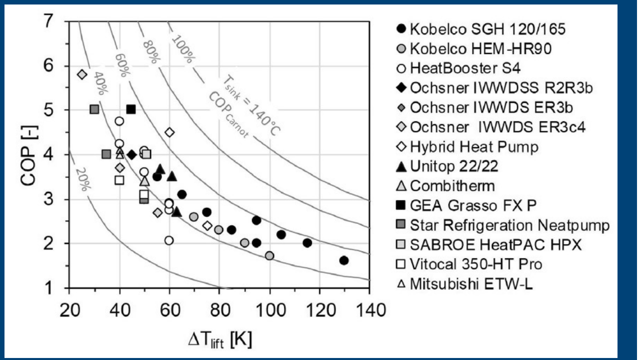
Conclusions

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



Aspagaus et al (2018)



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Questions




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