Industrial Heat Pumps

Supplier update, suitable refrigerants and application examples in food & steam generation

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AUSTRALIAN ALLIANCE FOR ENERGY PRODUCTIVITY

A2EP Briefing: Advances in industrial heat pumps
3 September 2020

IES INSTITUTE FOR ENERGY SYSTEMS

White Paper: Strenghtening Industrial Heat Pump Innovation

Link: White Paper

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Brian Elmegaard, DTU
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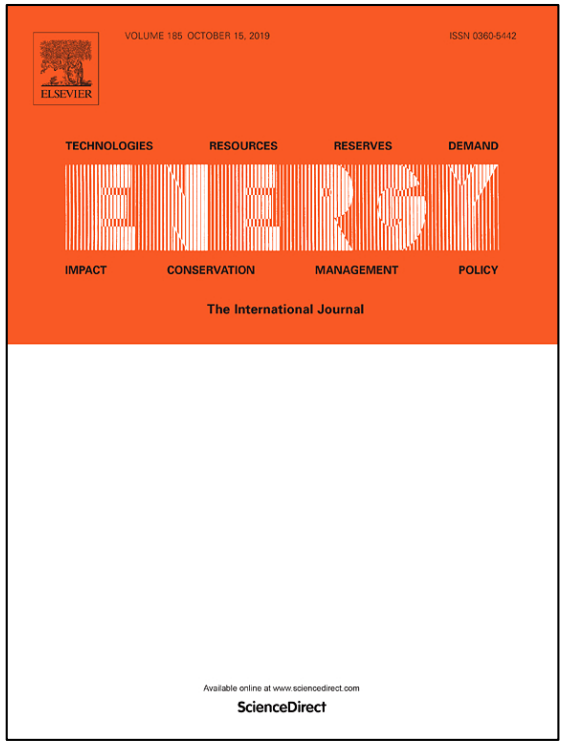
Review Papers

Arpagaus C., Bless F., Uhlmann M., Schiffmann J., Bertsch S.S.: **Review - High temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials**, Energy, 2018, 152, 985-1010



Arpagaus C., Bless F., Schiffmann J., Bertsch S.S.: **Multi-temperature heat pumps: A literature review**, International Journal of Refrigeration, 2016, 69, 437–465.

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Book «Hochtemperatur-Wärmepumpen» (in German)

Link: https://www.vde-verlag.de/buecher/494550/hochtemperatur-waermepumpen.html

Content

- Supplier update on industrial heat pumps
- Suitable refrigerants
- Application examples in food & steam generation

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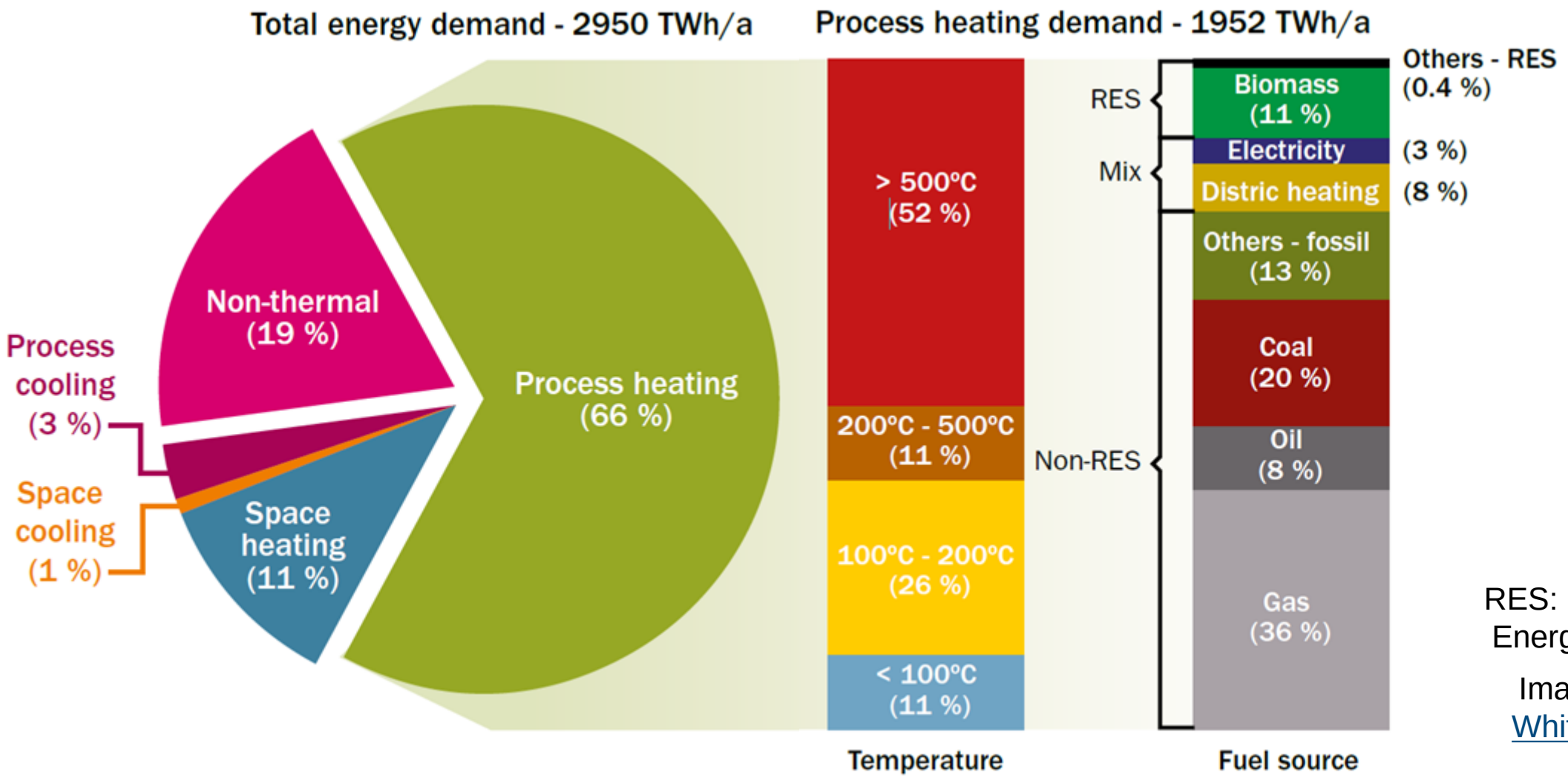
Process heat demand in the European industry by application, temperature level and fuel source



RES: Renewable Energy Sources

Image from White Paper

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CO_2 emission levels of different heating technologies and fuels

	CO_2 EMISSION PER KWH OF ENERGY ($g\ CO_{2equivalent}/kWh$)	EFFICIENCY OF TECHNOLOGY	CO_2 EMISSION PER KWH OF USEFUL HEAT ($g\ CO_{2equivalent}/kWh_{useful\ heat}$)
Gas condensing boiler	Gas: 242	eta = 95%	254
Gas non-condensing (eta = 85%)	Gas: 242	eta = 85%	284
Oil	Oil: 357	eta = 75%	476
Coal	Coal: 390	eta = 65%	612
Direct electric heating	Electricity: 400	eta = 100%	400
Heat pump (SPF 3)	Electricity: 400	eta = 300%	133
Heat Pump (SPF4)	Electricity: 400	eta = 400%	100
Heat Pump (SPF4) + electricity emission = 100	Electricity: 100	eta = 400%	25

Factor 10

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Efficient transformation of useful (waste) heat to higher temperatures

- Distillation 100 - 300°C
- Drying processes 40 - 250°C
- Evaporation 40 - 170°C
- Pasteurisation / Sterilisation 70 - 120°C
- ...

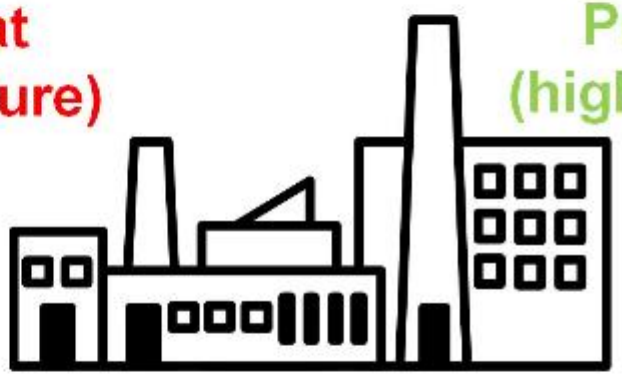
Heat pump efficiency

$$COP = \frac{\text{Useful heat}}{\text{Driving power}}$$

Process heat (high temperature)

Process heat (high temperature)

Primary energy (Gas, oil, coal, biomass)



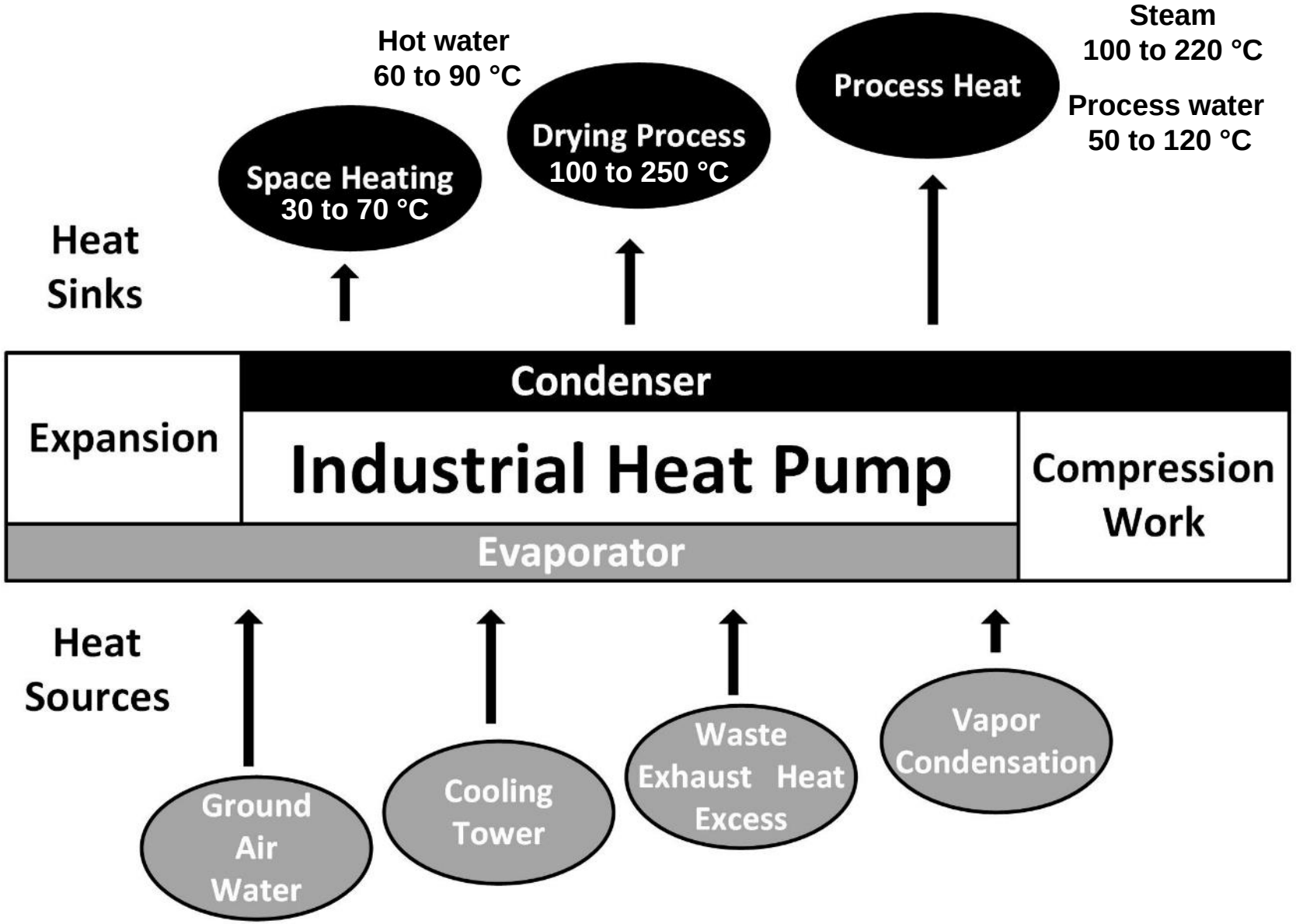
Industrial heat pump

Primary energy

- Exhaust air from ovens 20 – 100°C
- Waste compressed air 30 – 70°C
- Waste water 20 – 60°C
- Cooling water 20 – 50°C
- ...

Waste heat (low temperature)

Heat sources and sinks



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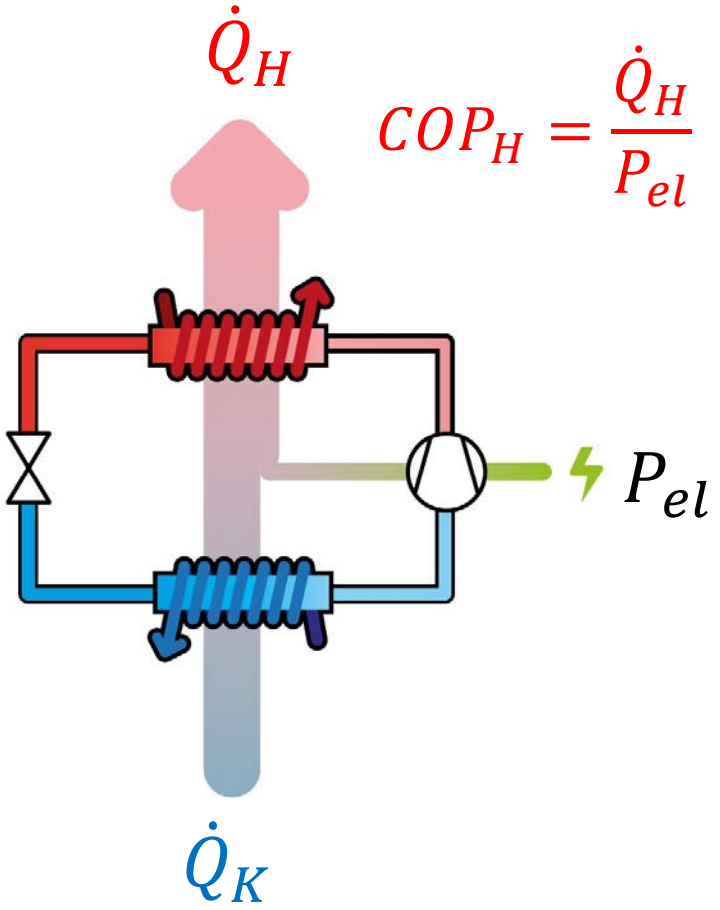
COP Heating:

$$COP_H = \frac{\dot{Q}_H}{P_{el}}$$



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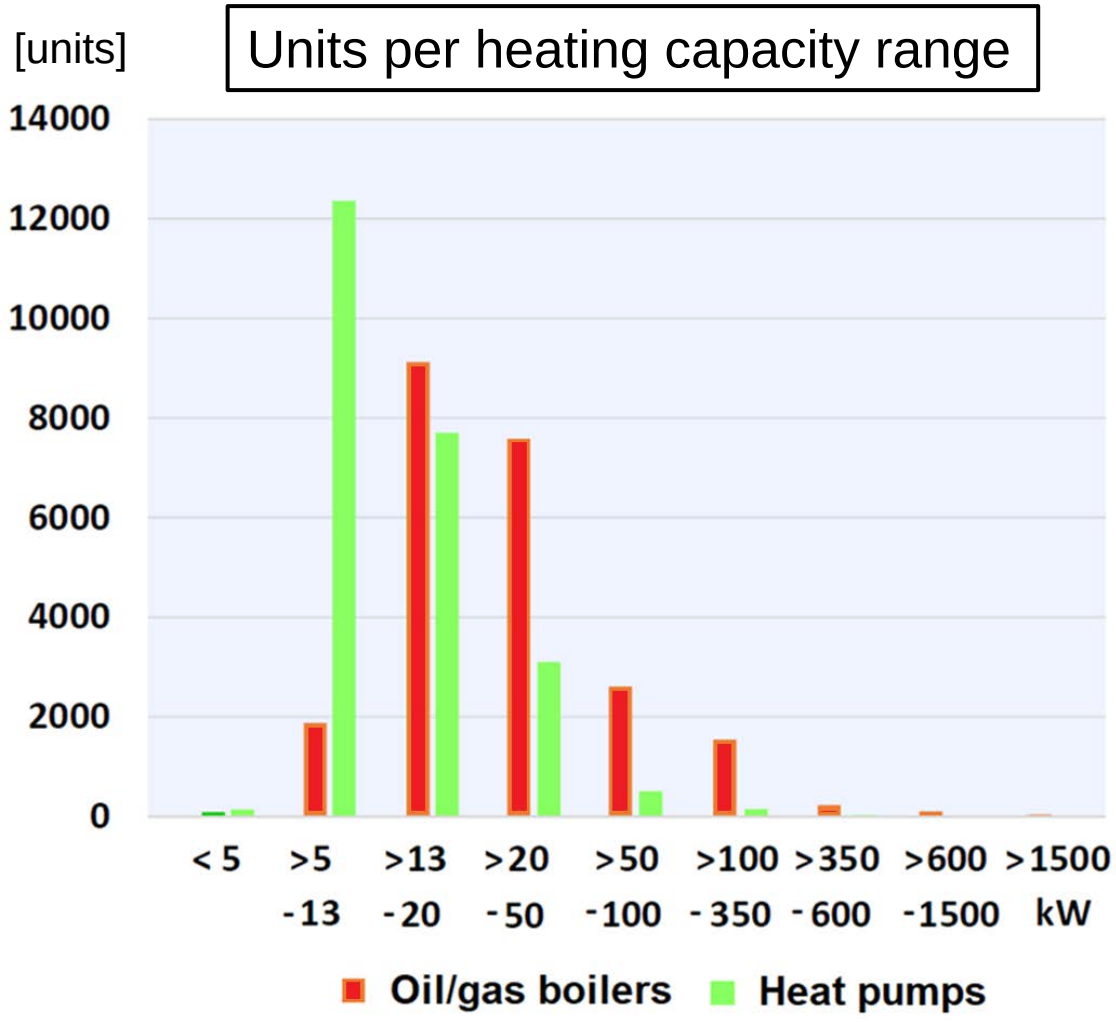
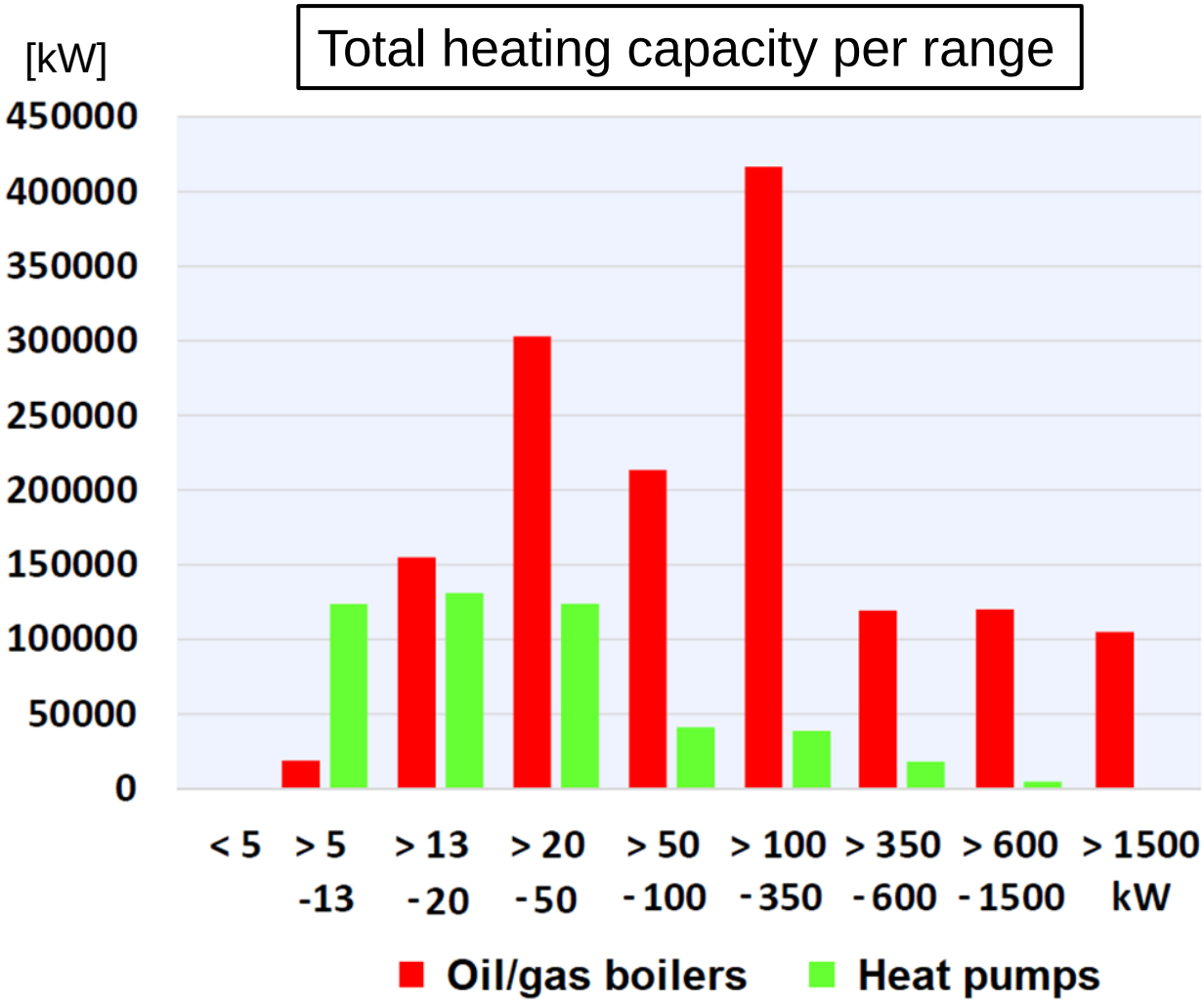
Switzerland 2019:
Distribution of sales figures by number and total heating capacity





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Challenges to further spread industrial heat pumps into the market

- **Low level of awareness of the technical possibilities and economically feasible application potential** of industrial heat pumps among users, consultants, investors, system planners, manufacturers and installers
- **Lack of knowledge about the integration** of heat pumps into existing industrial processes
- **Tailor-made designs**, i.e. small batch sizes (low economies of scale)
- **Longer amortization periods** than for gas or oil-fired boilers (required are ≤ 3 years). With lower electrical current and higher gas prices smaller amortization periods are reached.
- **Competing heating technologies** (with fossil fuels at low energy prices)
- **Requirements of heat storage** to compensate for the time lag between demand and supply (e.g. heat pump for band load, gas boiler for heating peaks)
- **Lack of available compressors** for high temperatures **and refrigerants** with low global warming potential (GWP) and zero ozone depletion potential (ODP)

Supplier update

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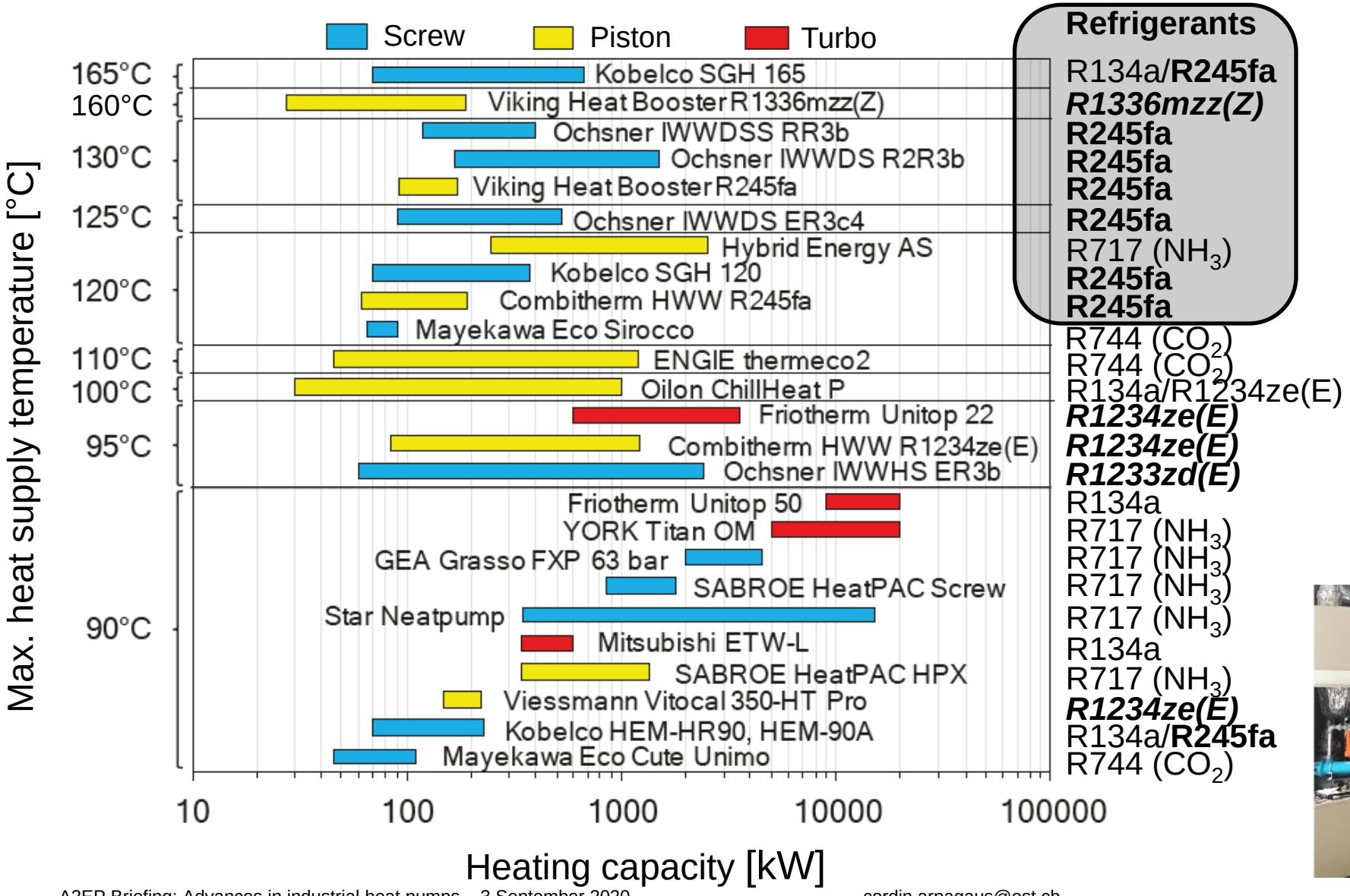
> 26 industrial HPs with heat supply ≥ 90 °C are commercially available



OCHSNER ENERGIE TECHNIK

HeatBooster S4 (Viking Heat Engines AS)

Kobelco SGH 120/165 (Steam Grow Heat Pump)

Selection of industrial heat pumps with heat pump cycles

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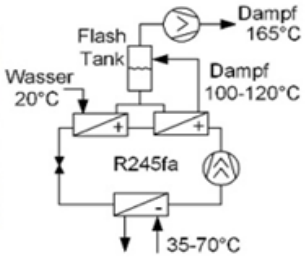
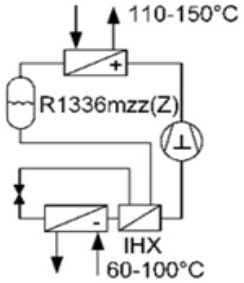
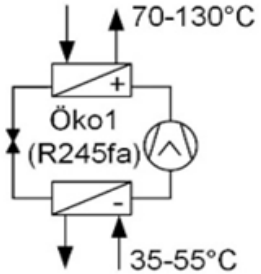
Kobe Steel
Kobelco SGH 120/165



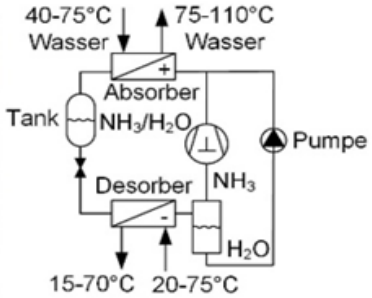
Viking Heat Engines
HeatBooster S4



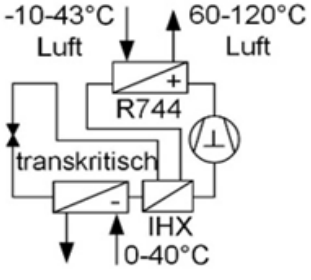
Ochsner
IWWDS ER3c4



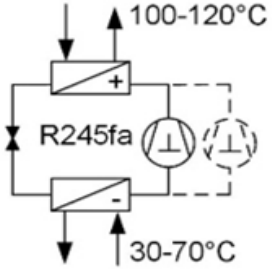
Hybrid Energy
Hybrid Heat Pump



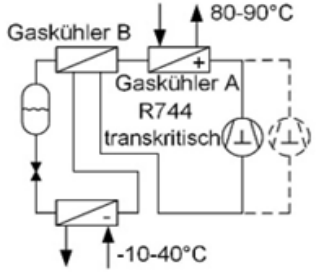
Mayekawa
Eco Sirocco



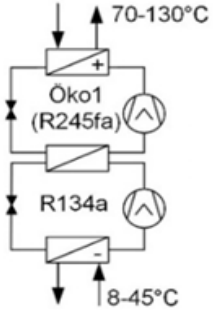
Combitherm
HWW R245fa



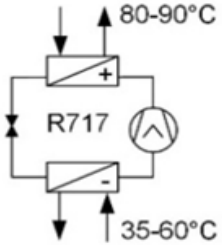
ENGIE (ex-Dürr Thermea), thermeco$_2$ HHR1000
mit 6 Hubkolbenverdichtern bis 1100 kW



Ochsner
IWWDSS R2R3b



Star Refrigeration, Neatpump NP601,
Vilter VSSH Schraubenkompressor 76 bar



Selection of industrial heat pumps with heat pump cycles

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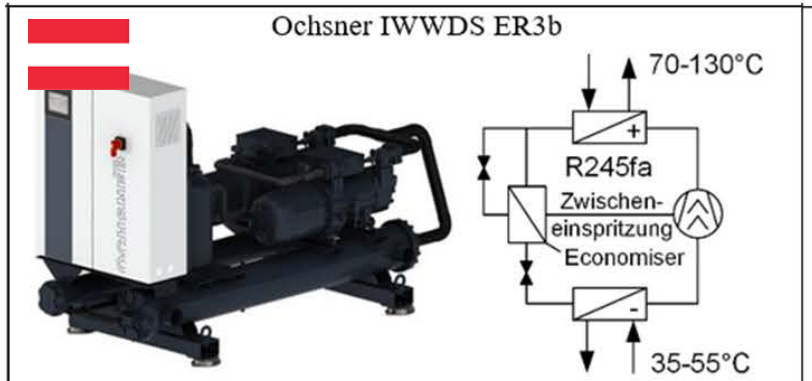

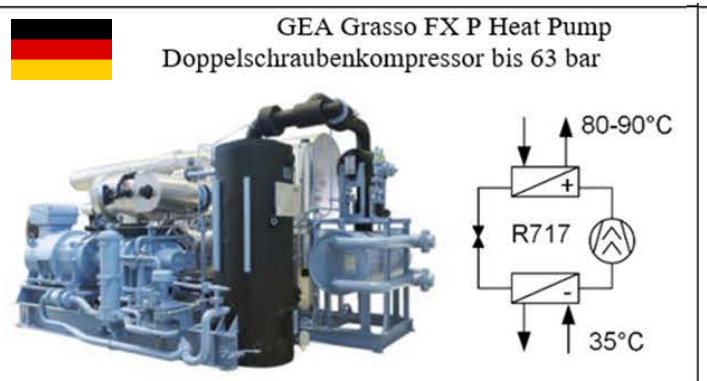

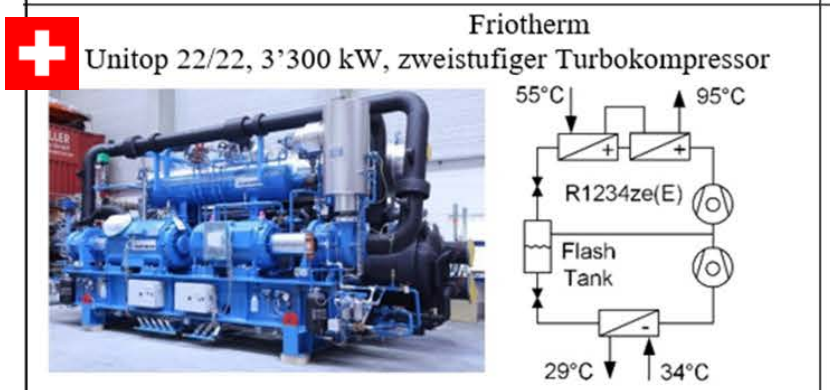

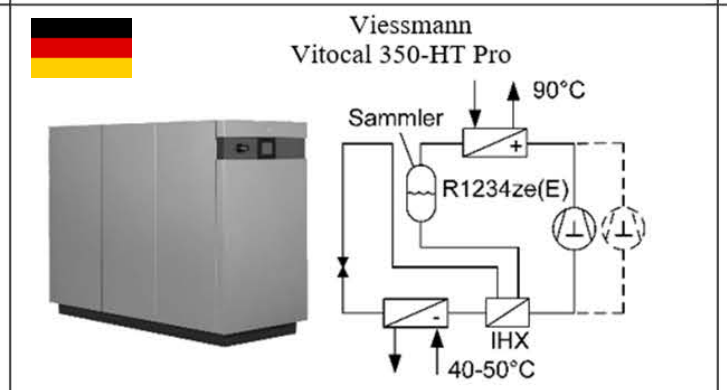

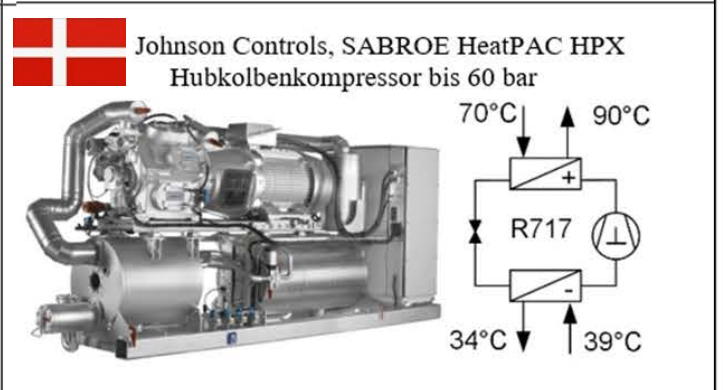

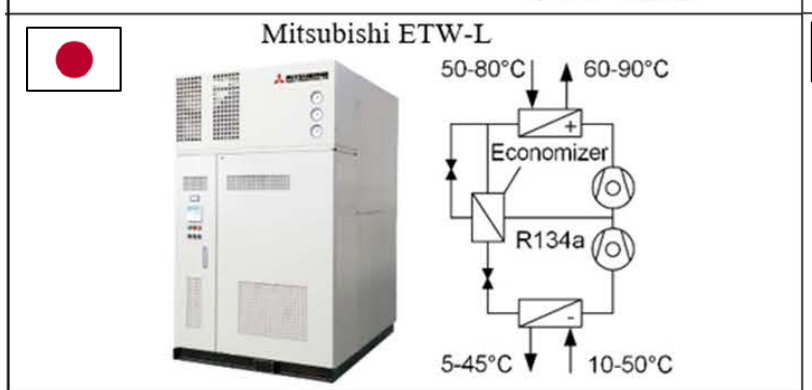

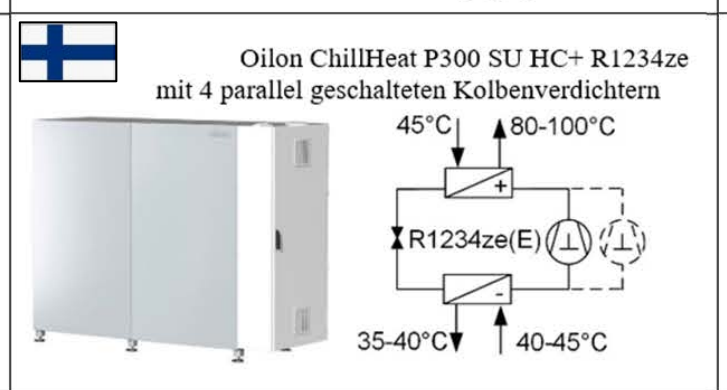

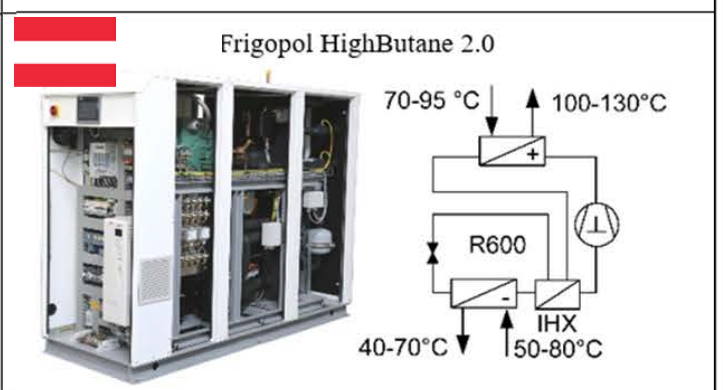

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Selection of industrial heat pumps with heat supply temperature ≥ 90 °C

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)

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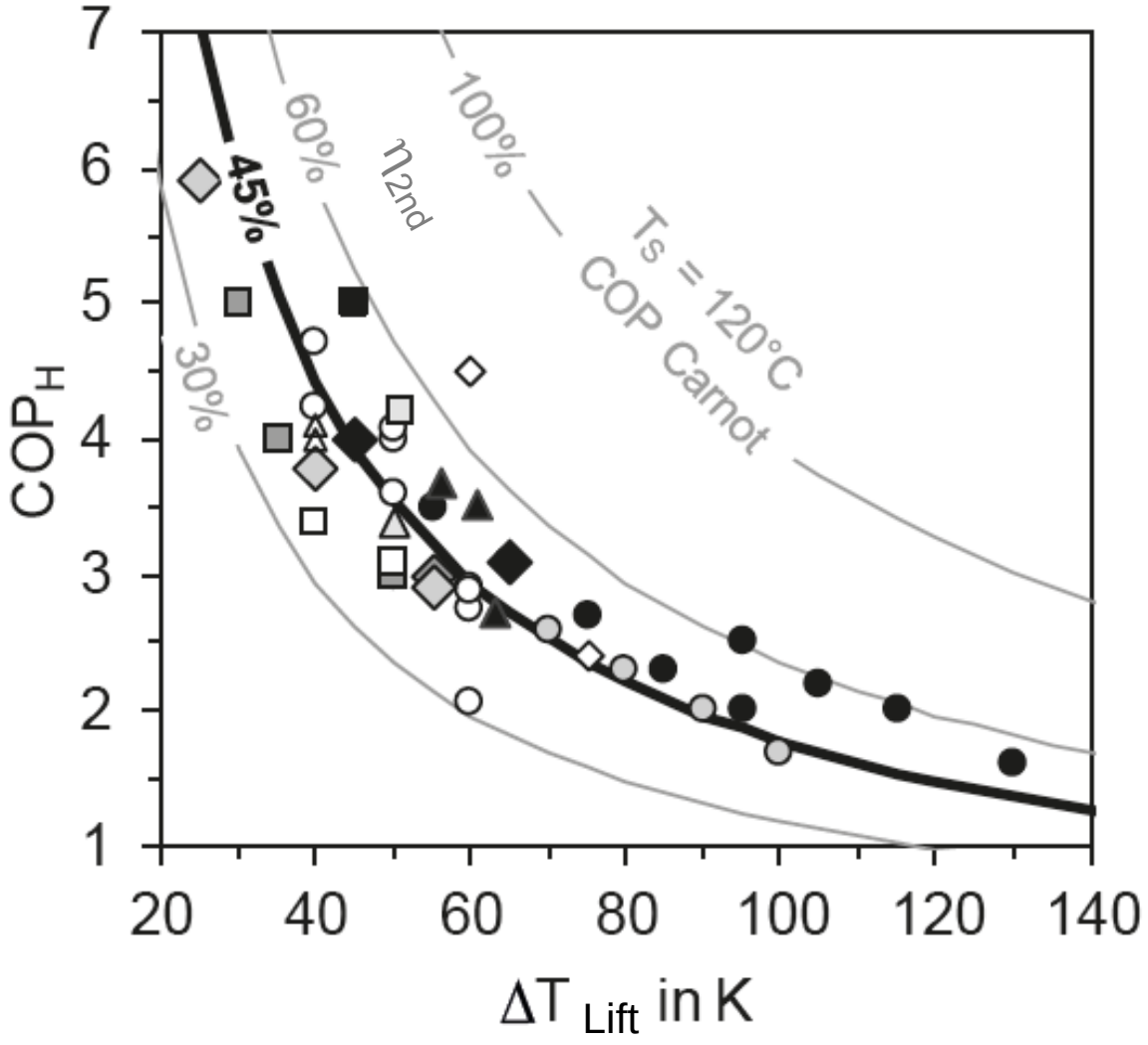
Efficiency (COP) range between 1.6 to 5.8 at temperature lifts of 130 to 30 K



$(= T_{Sink,out} - T_{Source,in})$

- ● Kobelco SGH 120/165
- ○ Kobelco HEM-HR90
- ○ Viking HeatBooster S4 R1336mzz(Z)
- ◆ Ochsner IWWDSS R2R3b
- ◇ Ochsner IWWDS ER3b
- ◇ Ochsner IWWDS ER3c4
- ◇ Hybrid Heat Pump
- ▲ Friotherm Unitop 22/22
- △ Combitherm
- ■ GEA Grasso FX P
- ■ Star Refrigeration Neatpump
- □ SABROE HeatPAC HPX
- □ Viessmann Vitocal 350-HT Pro
- △ Mitsubishi ETW-L

2nd Law efficiency:

$\eta_{2nd} = COP_H / COP_{Carnot}$

$$COP_{Carnot} = \frac{T_{Sink,out}}{T_{Sink,out} - T_{Source,in}}$$

Fit-curve (45% 2nd Law efficinecy η_{2nd}):

$COP_H = 68.455 \cdot \Delta T_{Lift}^{-0.76}$, $R^2 = 0.78$

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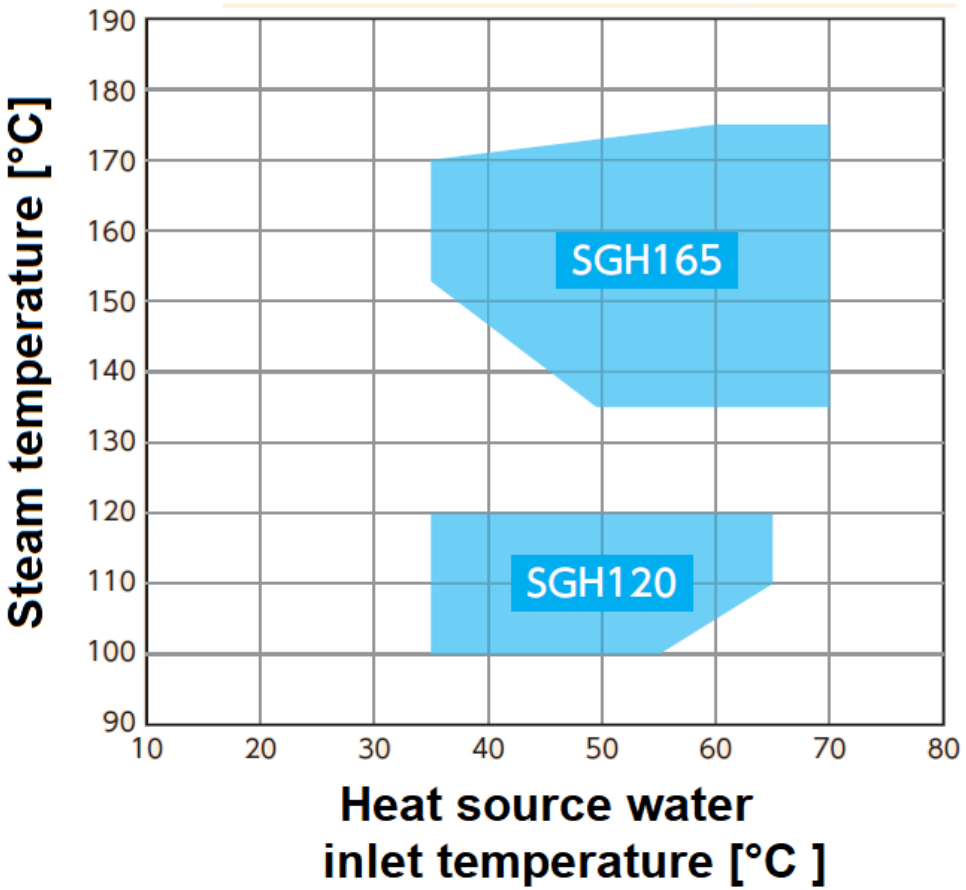
Steam Generating Heat Pump from Kobelco (Japan) (SGH120 und SGH165)



SGH120TF	SGH165FM
0.1MPaG	0.6MPaG
120℃	165℃
65℃	70℃
370kW	624kW
0.51t/hr	0.84t/hr
3.5	2.5
35~65℃	35~70℃
0.0~0.1MPaG	0.2~0.8MPaG

Link: https://www.kobelco.co.jp/products/download/machinery/files/kobelco_heatpump_sgh.pdf

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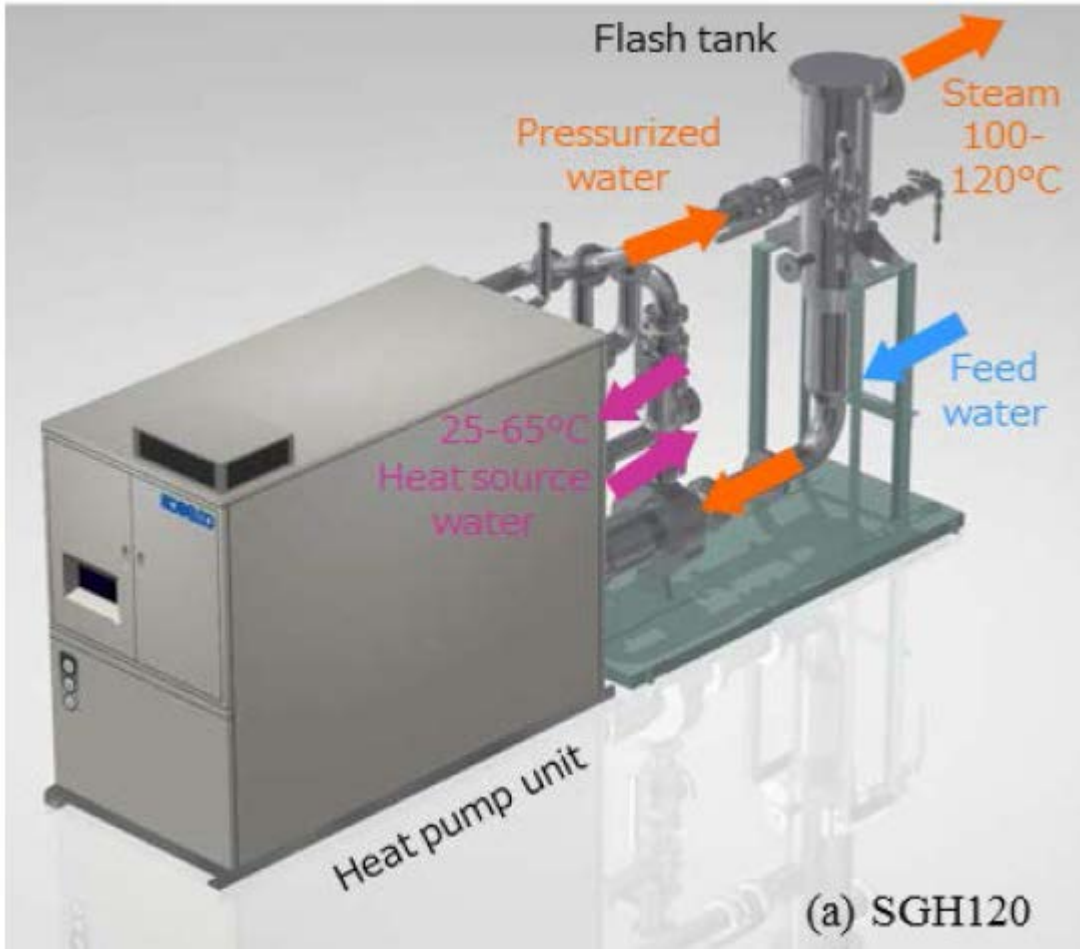
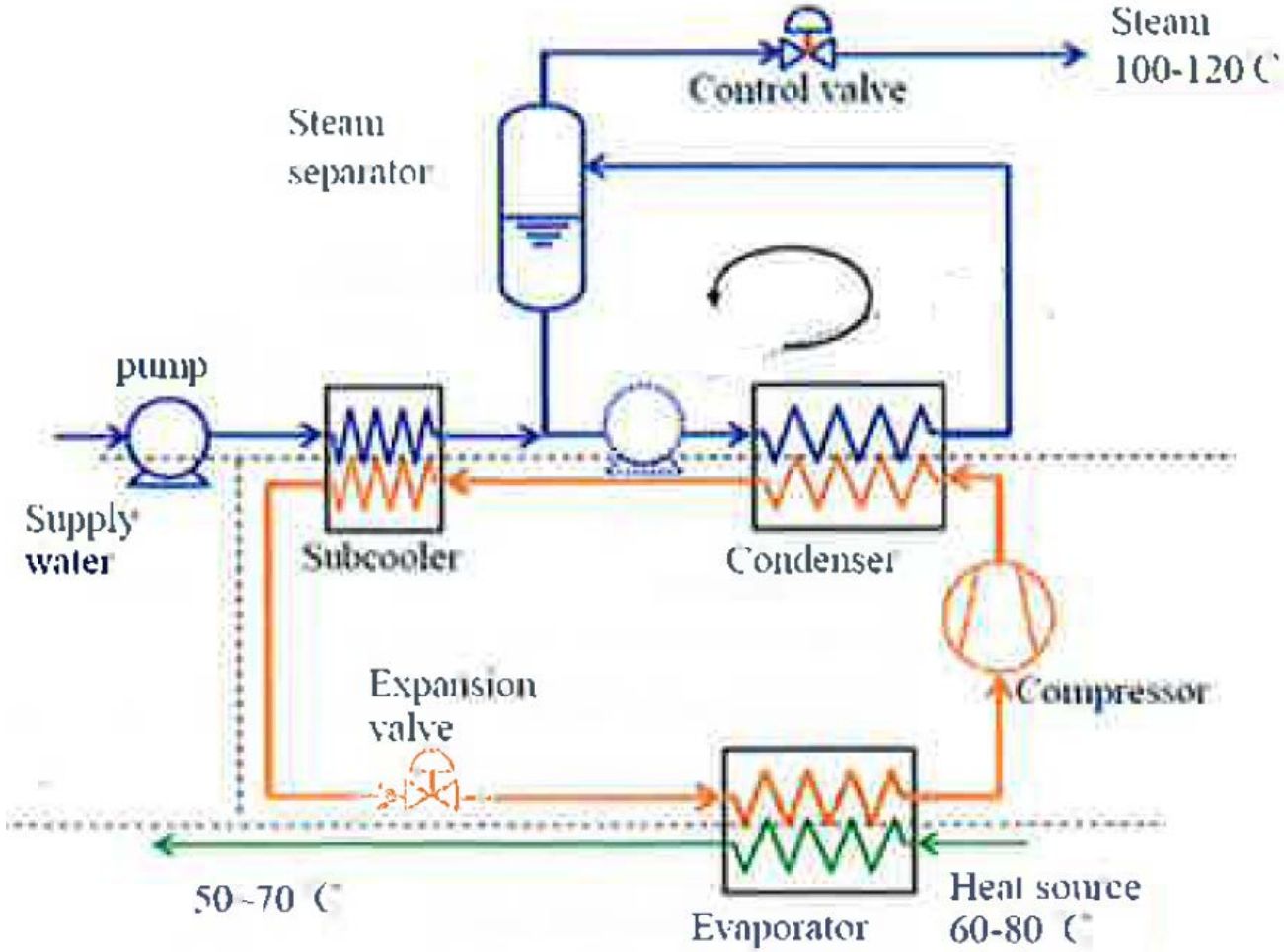
Steam Grow Heat Pump (SGH120 and SGH165) from Kobelco (Japan)



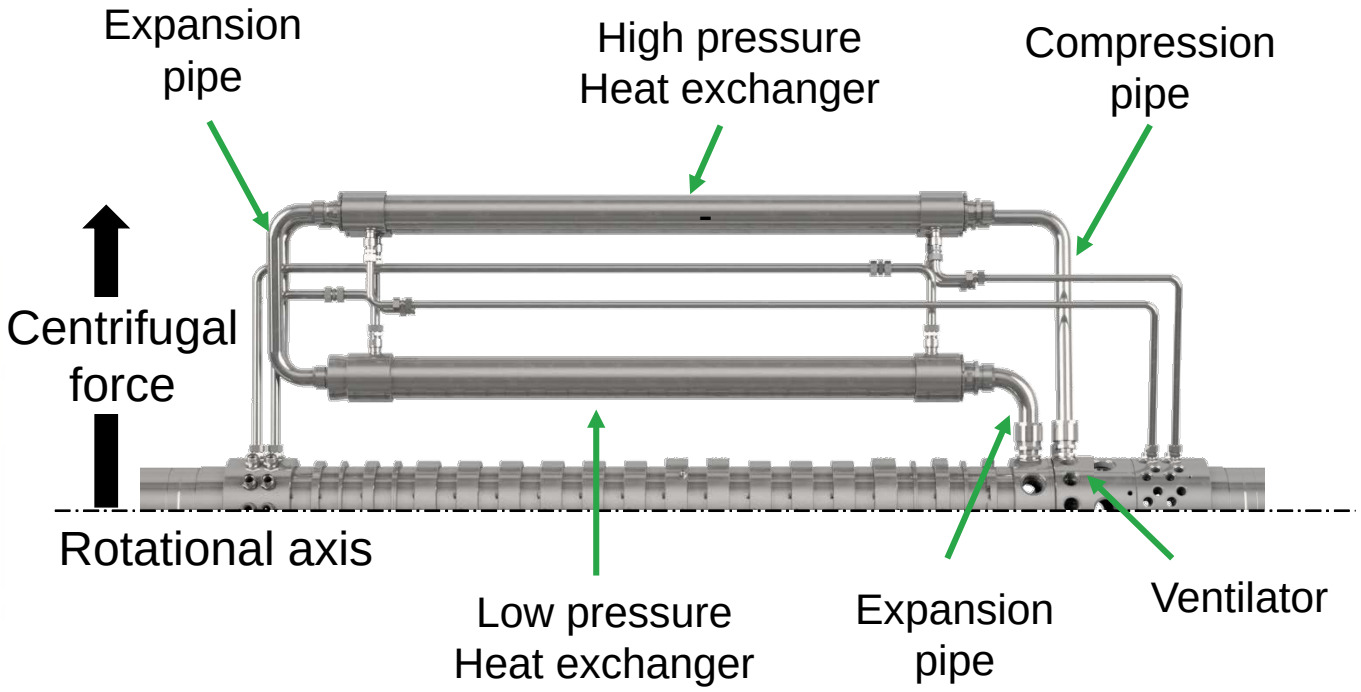


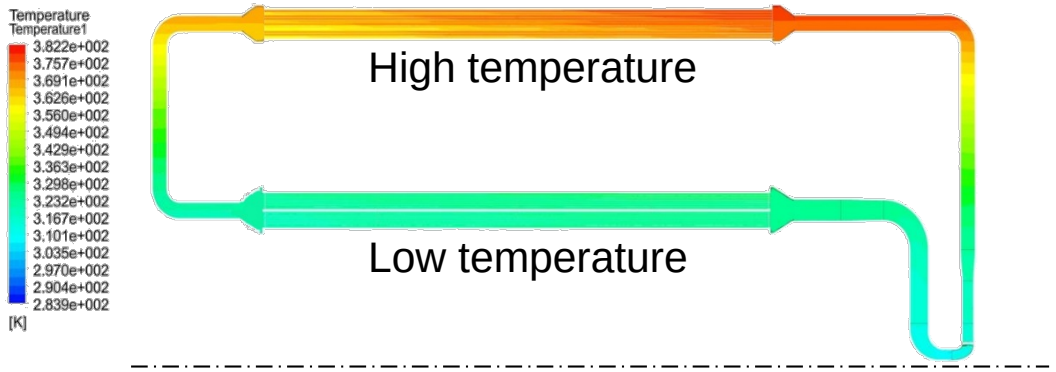
Link: https://www.kobelco.co.jp/products/download/machinery/files/kobelco_heatpump_sgh.pdf

Rotation Heat Pump of ecop Technologies GmbH (Austria)

- up to 150 °C, flexible temperature ranges
- (-20 °C to +150 °C), 700 kW heat output
- High COP, high temperature glides
- Noble gas as refrigerant, Joule process

www.ecop.at





SIEMENS
Ingenuity for life

Large scale high temperature heat pumps for district heating and industrial applications

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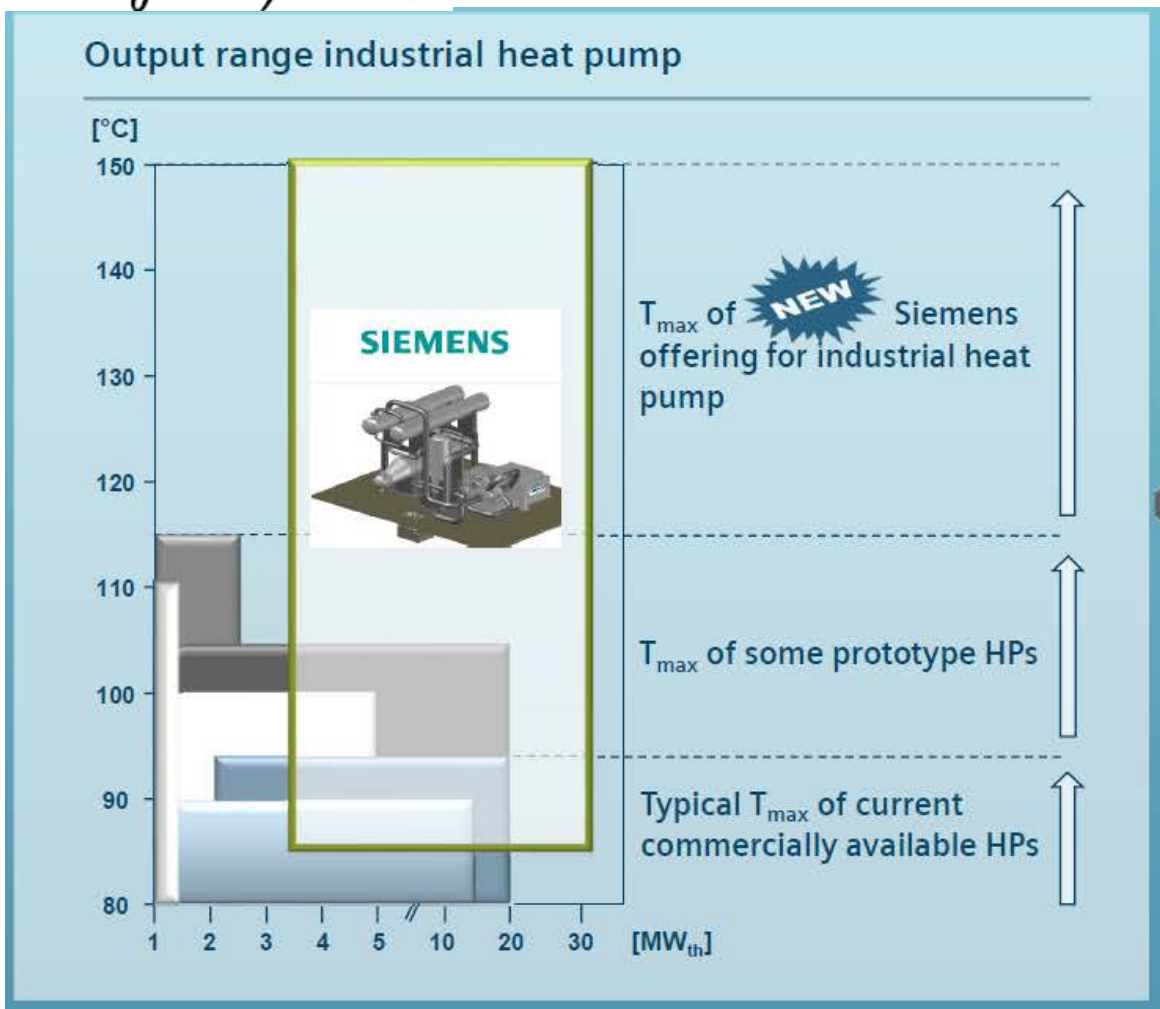
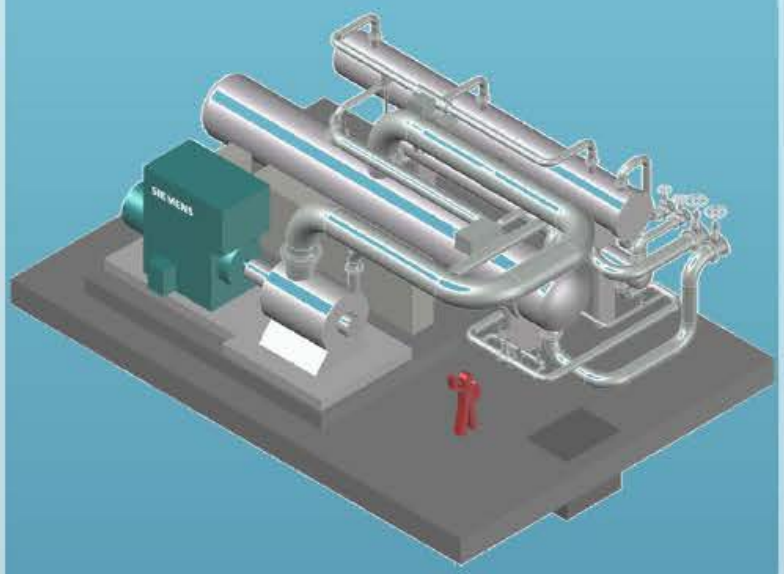


High temperature



Industrial Heat Pump

Heat supply

per unit
~ 4 - 35 MW_{th}

Temperatures

up to
~150°C

Various Drive Concepts

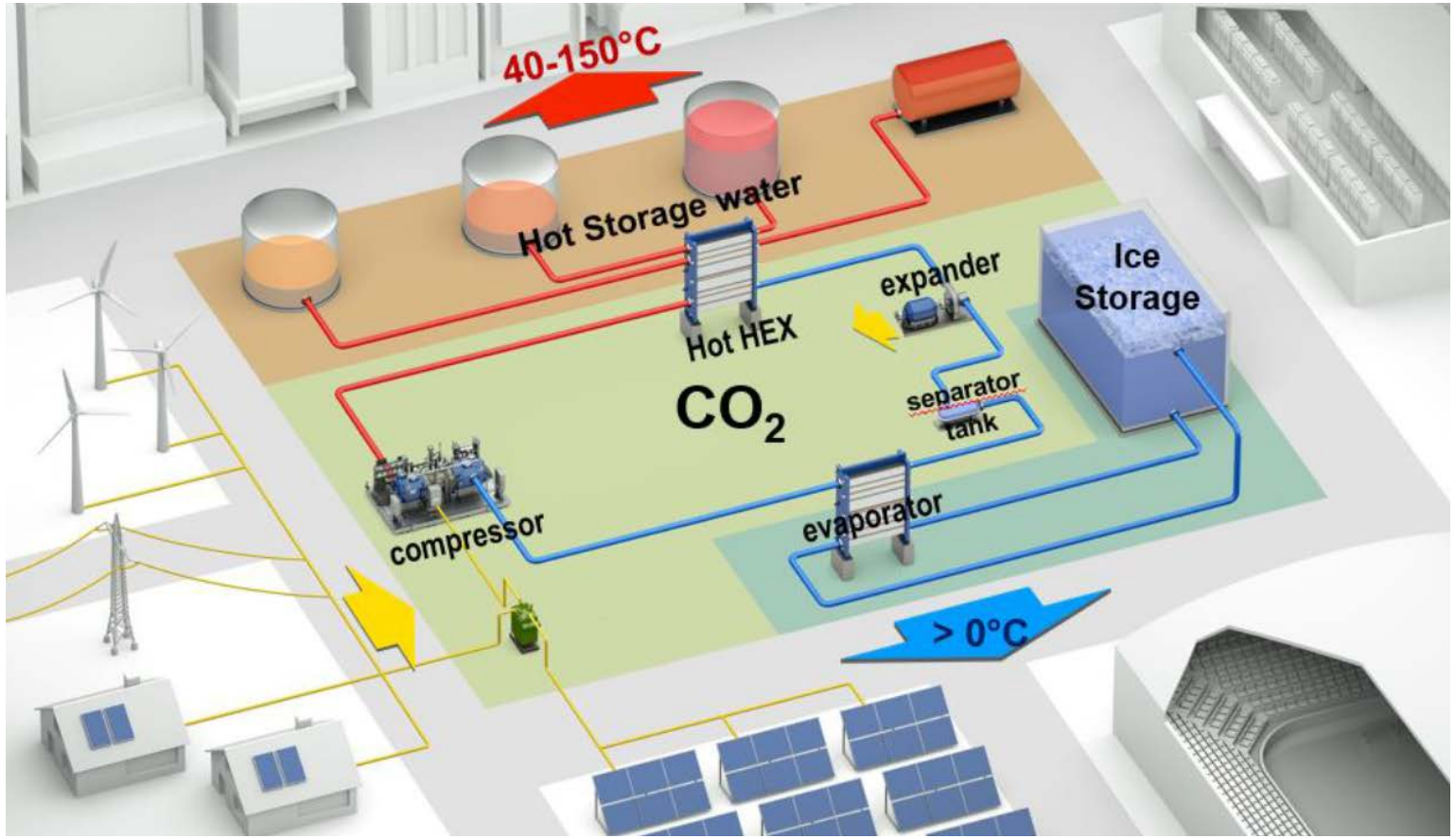
electrical
or mechanical

Scope of Supply

component up to
turnkey supply

Electro-thermal energy storage (ETES) from MAN Energy Solutions Schweiz AG
Modular high temperature heat pump on a large scale

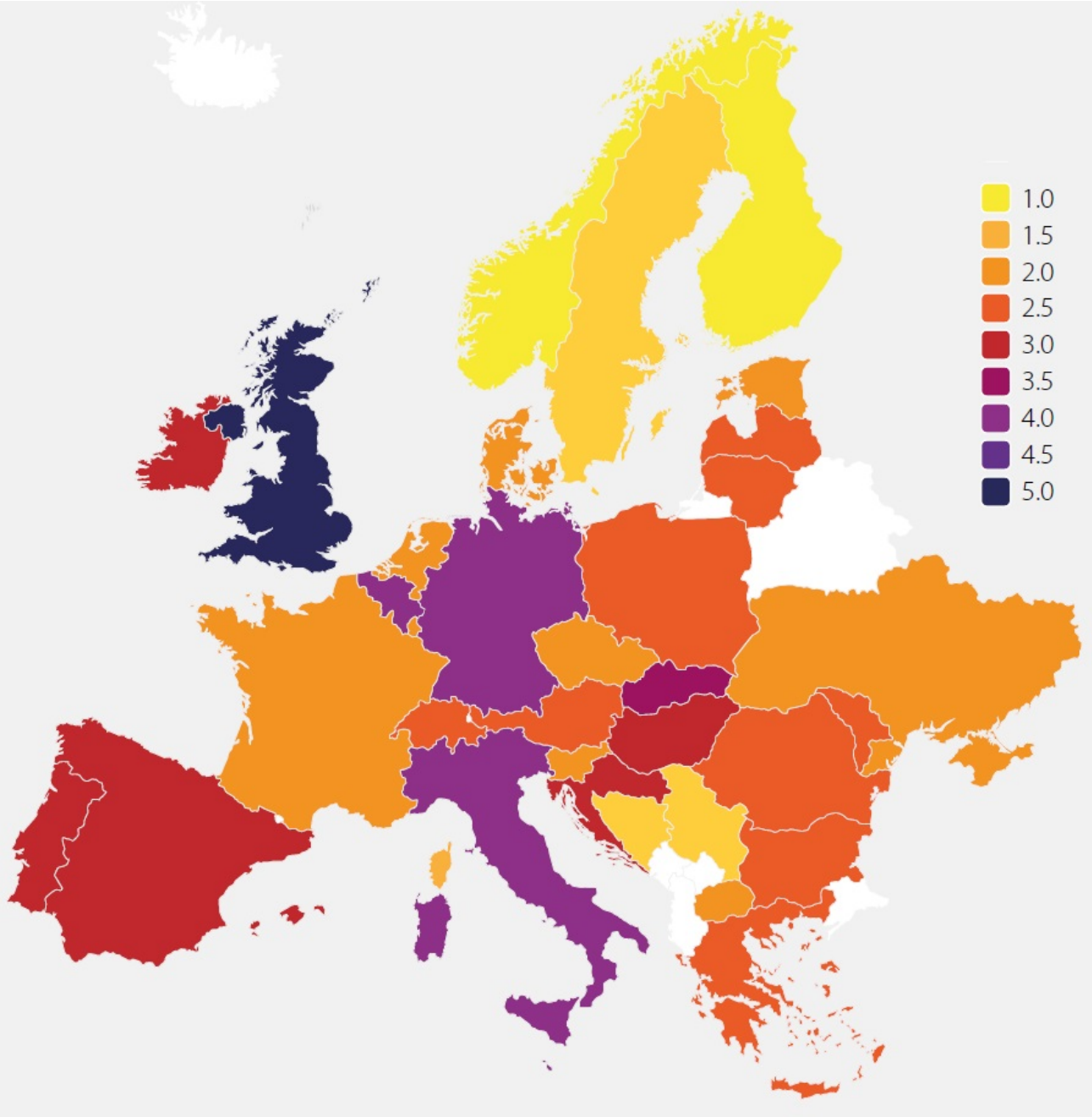
- Trigeneration (heat, cold, electricity), with storage possibilities
- 0 °C to 150 °C, modular from 5 to 100 MW_{th}
- CO_2 (R744) as refrigerant



HOFIM™ Kompressor
(**H**igh speed **O**il **F**ree **I**ntegrated **M**otor compressor)

Decorvet & Jacquemoud: 2nd Conference on High Temperature Heat Pumps, Copenhagen, 2019

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

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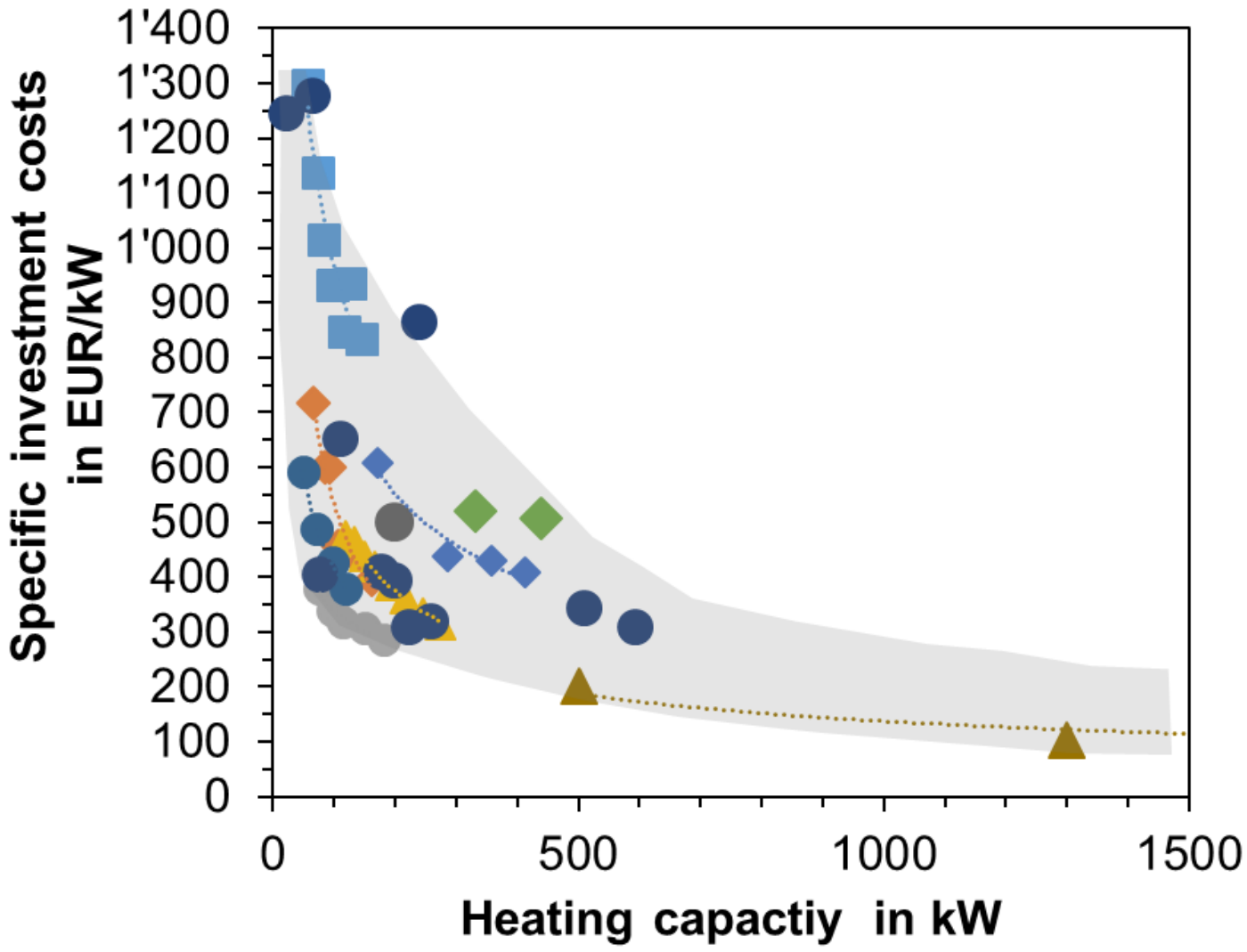
Specific investment costs (incl. installation) per kW of heating



Own figure based on price information from European heat pump suppliers

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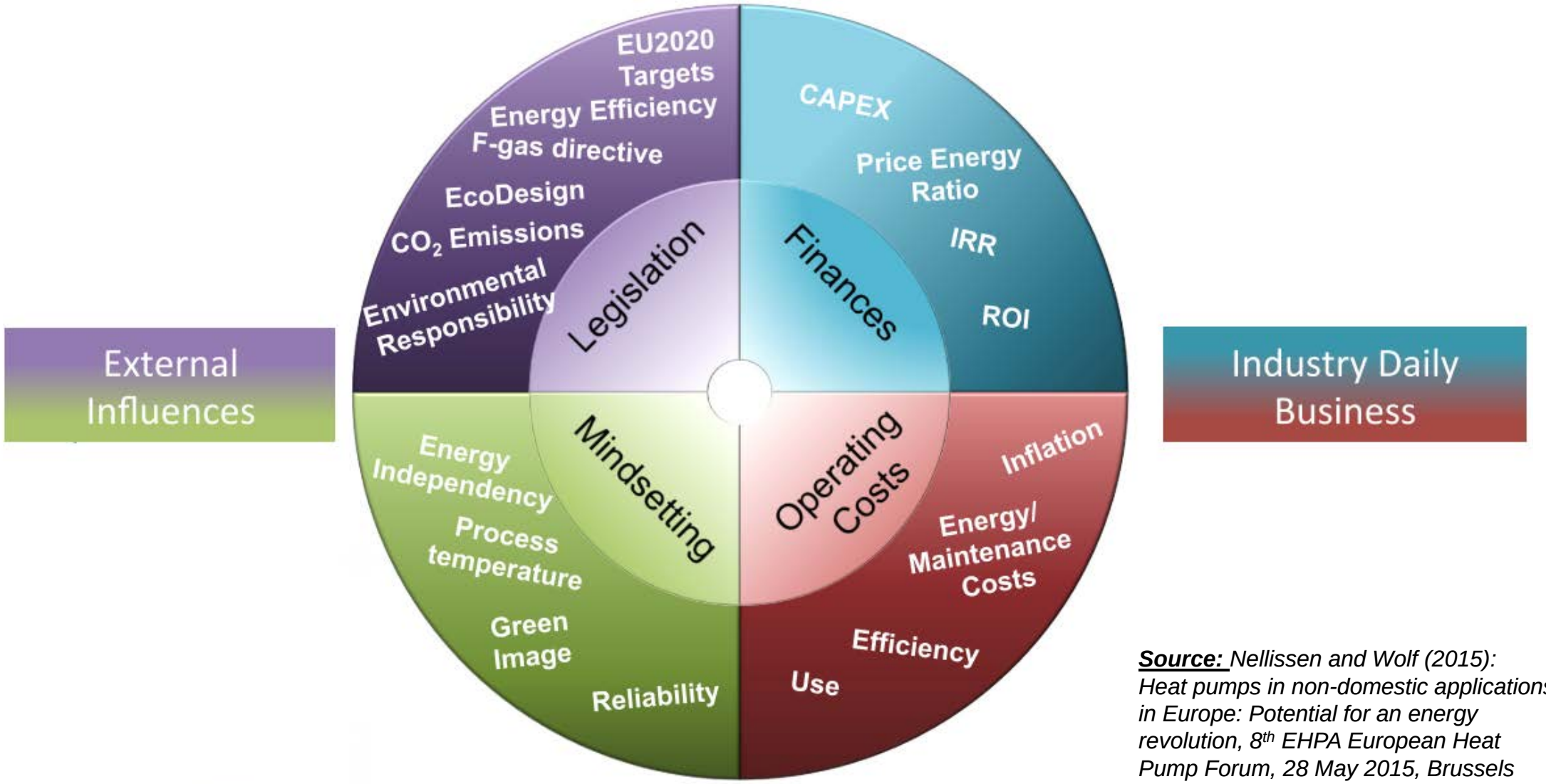
Drivers – Decisions factors



Source: *Nellissen and Wolf (2015): Heat pumps in non-domestic applications in Europe: Potential for an energy revolution, 8th EHPA European Heat Pump Forum, 28 May 2015, Brussels*

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Supplier Update – Market Overview

- **Large application potentials for HTWP (hot water, hot air, steam generation)**
- Particular in the **food, paper and chemical industries**, in processes like **drying, evaporation, sterilization, and heat recovery**
- Technical potential in **Europe: 113 PJ process heat** between **100 and 150°C**
- **> 26 HTHPs** (compression heat pumps) **from 15 manufacturers** identified on the market **with supply temperatures > 90°C** (some > 120°C, pioneers **max. 165°C**)
- **COPs: 2.4 to 5.8** with temperature lift from 40 to 95 K
- $\mathbf{COP_H = 68.455 \cdot \Delta T_{Lift}^{-0,76}}$ (H: heating, ΔT_{Lift} from heat source to heat sink in K, at 45% 2nd Law efficiency)
- **Heating capacity: 20 kW to 20 MW**
- Refrigerants: **R245fa, R717 (NH_3), R744 (CO_2), R134a, R1234ze(E), R1336mzz(Z)**
- Compressors: 1- and 2-shaft **screws**, 2-stage **turbos**, **piston** (parallel)
- Cycles: **typically 1-stage**, optimization with **IHX**, **parallel compressors**, **economizer**, **2-stage cascade** (R134a/R245fa)

Suitable Refrigerants

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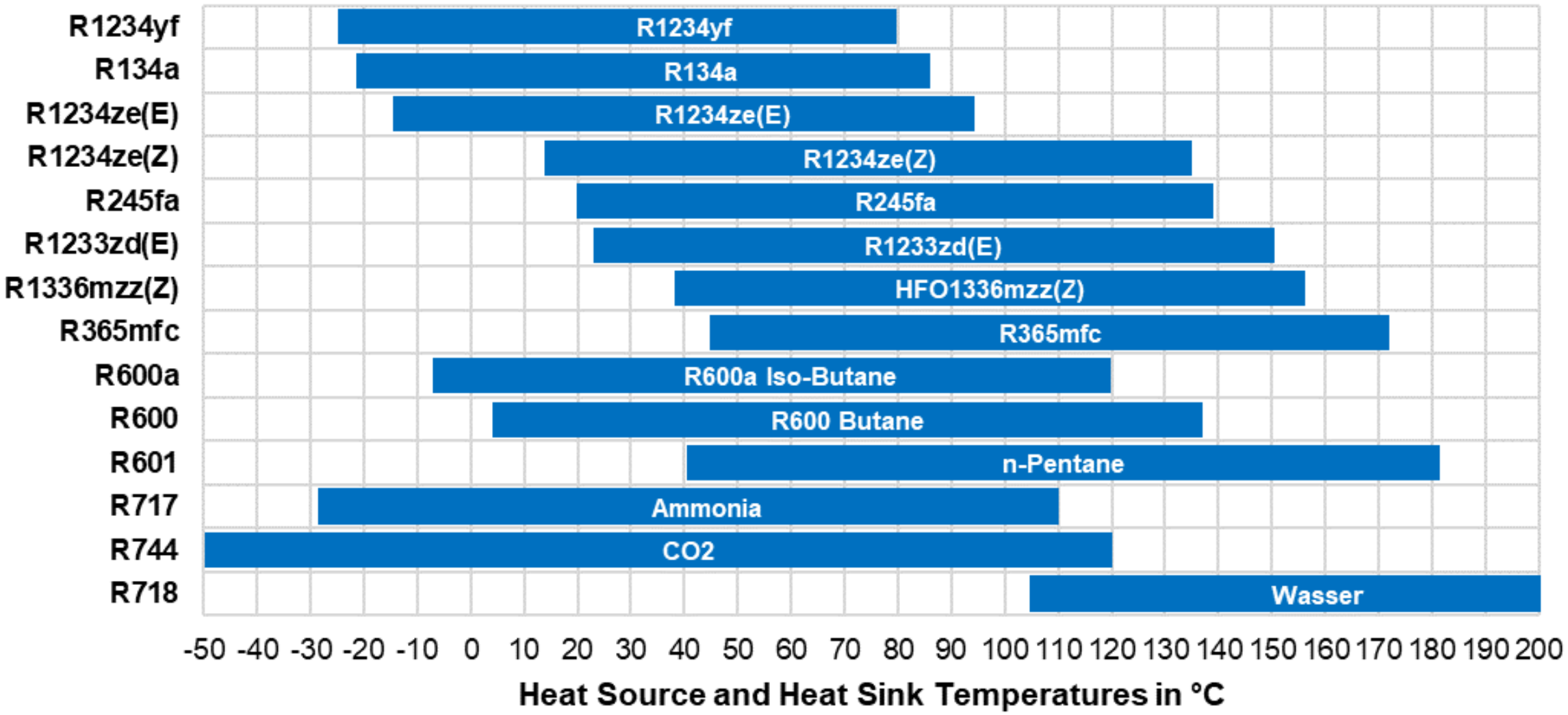
FHO Fachhochschule Ostschweiz

Range of use of different refrigerants for high temperature heat pumps



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The 4th generation of synthetic low GWP refrigerants for chiller, ORC, and HTHP applications

Montréal Protocol (1987)

CFC (R113)

Ozone layer depletion

Regulation (2037/2000)

HCFC (R123)

Kyoto Protocol (1997)

HFC (R245fa)

Global warming greenhouse gases

EU F-Gas Regulation (517/2014)

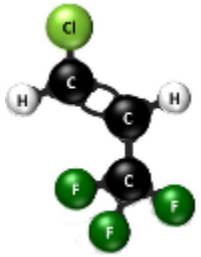
Paris Agreement (2015)

Kigali Amendment (2019)

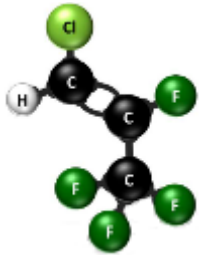
Cost increase

HFO (R1336mzz(Z)) HCFO (R1233zd(E), R1224yd(Z))

R1336mzz(Z)



R1233zd(E)



R1224yd(Z)

Criteria :

- low GWP
- short atm. lifetime
- zero/low ODP
- low flammability
- high efficiency
- high T_{crit}

CFC: fully halogenated chlorofluorocarbons
HCFC: partially halogenated chlorofluorocarbons
HFC: hydrofluorocarbons
HFO: hydrofluoroolefins
HCFO: hydrochlorofluoroolefins

These refrigerants have a global warming potential (GWP) of 10 and less

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Refrigerant manufacturers and products for HTWP

R1233zd(E)
Solstice®zd
Honeywell
R245fa
Genetron® 245fa

R1336mzz(Z)
Opteon™ MZ
Chemours

R1233zd(E)
FORANE HTS 1233ZD
ARKEMA
INNOVATIVE CHEMISTRY

R1224yd(Z)
AMOLEA®1224yd
AGC Chemicals

3M™ Novec™ 649

R365mfc
Solkane®365mfc
SOLVAY
asking more from chemistry®

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Selection criteria

Criteria	Required properties
Thermal suitability	High critical temperature (>150 °C), low critical pressure (<30 bar)
Environmental	ODP = 0, low GWP (<10), short atmospheric life
Safety	Non-toxic, non-combustible (safety group A1)
Efficiency	High COP, low pressure ratio, minimal overheat to prevent fluid compression, high volumetric capacity
Availability	Available on the market, low price
Other factors	Good solubility in oil, thermal stability of the refrigerant-oil mixture, lubricating properties at high temperatures, material compatibility with steel, aluminum and copper

Data sources: Bertinat (1986), Burtscher et al. (2009), Calm (2008), Eisa et al. (1986), Göktun (1995), Helminger et al. (2016), Klein (2009), Kujak (2016), Reißner et al. (2013), Rieberer et al. (2015)

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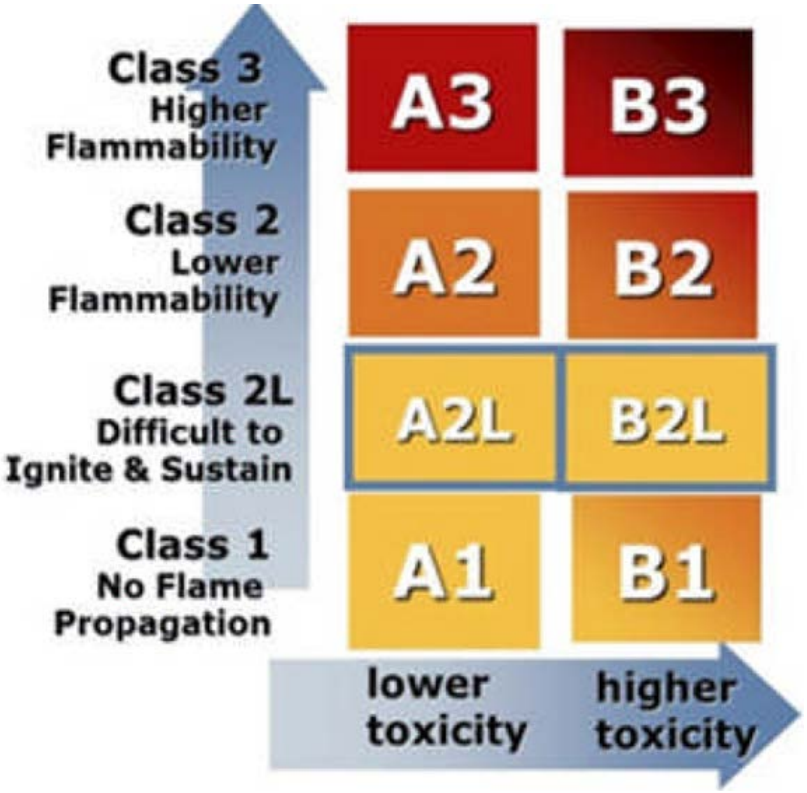
Safety Group Classification according to DIN EN 378-1 (2008) and ASHRAE 34



Flammability					
	higher	A3	R290, R1270, R601, R600, R600a, E170	B3	
	lower	A2	R152a, R365mfc, SES36, R1234ze(Z), R1234ze(E), R1234yf	B2	R717
	no flame propagation	A1	R113, R114, R134a, R236fa, R227ea, R410A, R1336mzz(Z), R1233zd(E), DR-14, DR-12, R718, R744	B1	R245ca, R245fa
		lower		higher	
		Toxicity			

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Refrigerant properties

Type	Refrigerant	Description	Chemical Formula	T_{crit} [°C]	p_{crit} [bar]	ODP [-]	GWP [-]	SG	NBP [°C]	M [g/mol]	Relative price [-]
CFC	R113	1,1,2-Trichloro-1,2,2-trifluoroethane	CCl_2FCClF_2	214.0	33.9	0.85	5'820	A1	47.6	187.4	Prohibited accoding to Montréal Protocol
	R114	1,2-Trichloro-1,1,2,2-tetrafluoroethane	$CClF_2CClF_2$	145.7	32.6	0.58	8'590	A1	3.8	170.9	
HCFC	R123	2,2-Dichloro-1,1,1-trifluoroethane	$C_2HCl_2F_3$	183.7	36.6	0.03	79	B1	27.8	152.9	
	R21	Dichlorofluoromethane	$CHCl_2F$	178.5	51.7	0.04	148	B1	8.9	102.9	
	R142b	1,1-Dichloro-1-fluoroethane	CH_3CCl_2F	137.1	40.6	0.065	782	A2	-10.0	100.5	
	R124	1-Chloro-1,2,2,2-tetrafluoroethane	C_2HClF_4	126.7	37.2	0.03	527	A1	-12.0	136.5	
HFC	R365mfc[a]	1,1,1,3,3-Pentafluorobutane	$CF_3CH_2CF_2CH_3$	186.9	32.7	0	804	A2	40.2	148.1	8.9
	SES36[b]	R365mfc/perfluoro-polyether	R365mfc/PFPE (65/35)	177.6	28.5	0	3'126[c]	A2	35.6	184.5	10.5
	R245ca	1,1,2,2,3-Pentafluoropropane	$CHF_2CF_2CH_2F$	174.4	39.3	0	716	n.a	25.1	134.0	n.a.
	R245fa[d]	1,1,2,2,3-Pentafluoropropane	$CHF_2CH_2CF_3$	154.0	36.5	0	858	B1	14.9	134.0	6.6
	R236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	124.9	32.0	0	8'060	A1	-1.4	152.0	10.2
	R152a	1,1-Difluoroethane	CH_3CHF_2	113.3	45.2	0	138	A2	-24.0	66.1	n.a.
	R227ea	1,1,1,2,3,3,3-Heptafluoropropane	CF_3CHFCF_3	101.8	29.3	0	3'350	A1	-15.6	170.0	6.9
	R134a	1,1,1,2-Tetrafluoroethane	CH_2FCF_3	101.1	40.6	0	1'300	A1	-26.1	102.0	1.2
	R410A	R32/R125 (50/50 mixture)	CH_2F_2/CHF_2CF_3	72.6	49.0	0	2'088	A1	-51.5	72.6	2.9
HFO	R1336mzz(Z)[e]	1,1,1,4,4,4-Hexafluoro-2-butene	$CF_3CH=CHCF_3(Z)$	171.3	29.0	0	2	A1	33.4	164.1	n.a.
	R1234ze(Z)	cis-1,3,3,3-Tetrafluoro-1-propene	$CF_3CH=CHF(Z)$	150.1	35.3	0	<1	A2L[f]	9.8	114.0	n.a.
	R1336mzz(E)[g]	trans-1,1,1,4,4,4,-Hexafluoro-2-butene	$CF_3CH=CHCF_3(E)$	137.7	31.5	0	18	A1	7.5	164.1	n.a.
	R1234ze(E)	trans-1,3,3,3-Tetrafluoro-1-propene	$CF_3CH=CHF(E)$	109.4	36.4	0	<1	A2L	-19.0	114.0	5.6
	R1234yf	2,3,3,3-Tetrafluoro-1-propene	$CF_3CF=CH_2$	94.7	33.8	0	<1	A2L	-29.5	114.0	13.8
HCFO	R1233zd(E)[h]	1-chloro-3,3,3-Trifluoro-propene	$CF_3CH=CHCl(E)$	166.5	36.2	0.00034	1	A1	18.0	130.5	6.3
	R1224yd(Z)[i]	1-chloro-2,3,3,3-Tetrafluoro-propene	$CF_3CF=CHCl(Z)$	155.5	33.3	0.00012	<1	A1	14.0	148.5	n.a.
HC	R601	Pentane	$CH_3CH_2CH_2CH_2CH_3$	196.6	33.7	0	5	A3	36.1	72.2	4.9
	R600	Butane	$CH_3CH_2CH_2CH_3$	152.0	38.0	0	4	A3	-0.5	58.1	1.8
	R600a	Isobutane	$CH(CH_3)_2CH_3$	134.7	36.3	0	3	A3	-11.8	58.1	1.0
	R290	Propane	$CH_3CH_2CH_3$	96.7	42.5	0	3	A3	-42.1	44.1	1.1
	R1270	Propene	$CH_3CH=CH_2$	91.1	45.6	0	2	A3	-47.6	42.1	1.0
CF6	Novec 649[j]	Dodecafluoro-2-methyl-3-pentanone	$CF_3CF_2C(O)CF(CF_3)_2$	168.7	18.8	0	<1	n.a.	49.0	316.0	6.8
Ether	E170	Dimethyl ether	CH_3OCH_3	127.2	53.4	0	1	A3	-24.8	46.1	39.0
Natural	R718	Water	H_2O	373.9	220.6	0	0	A1	100.0	18.0	5.6[k]
	R717	Ammonia	NH_3	132.3	113.3	0	0	B2L	-33.3	17.0	27
	R744	Carbon dioxide	CO_2	31.0	73.8	0	1	A1	-78.5	44.0	1.0

excluded

suitable

HFCs for comparison

CFC = Chlorofluorocarbons, HCFC = Hydrochlorofluorocarbons, HFC = Hydrofluorocarbons, HFO = Hydrofluoroolefins, HCFO = Hydrochlorofluoroolefins, HC = Hydrocarbons, T_{crit} = critical temperature, p_{crit} = critical pressure, ODP = Ozone Depletion Potenial (R11=1.0, UNEP, 2017), GWP_{100} = Global Warming Potential (CO_2=1.0, 100 years, EU F-Gas Regulation 517/2014, Myhre et al., 2013), SG = Safety Group (DIN EN 378-1, 2008, ASHRAE 34), NBP = Boiling point at 1.013 bar, *M* = Molecular weight, Relativer price per kg refrigerant compared to CO_2 of 9 Euro/kg (based on a 10 kg vessel, October 2017), n.a. = price not yet available but close to market, Solkane®365mfc from Solvay, [b]Solkatherm®SES36 from Solvay, [c]Lewandowski et al. (2010), [d]R245fa from Linde or Honeywell (Genetron® 245fa).[e]Opteon™ MZ from Chemours, [f]Fukuda et al. (2014), [g]Juhasz (2017), [h]Solstice®zd from Honeywell, [i]AMOLEA® 1224yd from AGC Chemicals, [j]Novec™ 649 from 3M, [k]Molecular biological quality

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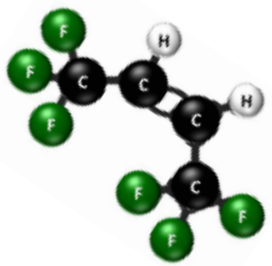
Properties of suitable HFO and HCFO refrigerants for HTHPs

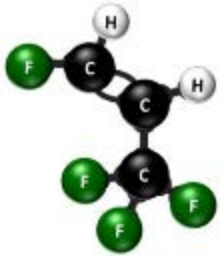
Tested at NTB Buchs

Refrigerant	Brand (manufacturer)	T_{crit} [°C]	p_{crit} [bar]	ODP [-]	GWP_{100} [-]	Lifetime [days]	SG	NBP [°C]
R1336mzz(Z)	**Opteon™ MZ (Chemours)**	**171.3**	**29.0**	**0**	**2[a]**	**22[a]**	**A1**	**33.4**
R1234ze(Z)[b]	Not yet available	150.1	35.3	0	<1[a]	10[a], 18[b]	A2L	9.8
R1233zd(E)	**Solstice®zd (Honeywell) Forane®HTS 1233zd (ARKEMA)**	**165.6**	**35.7**	**0.00034[d], 0.00030[e]**	**1[a], <5[e]**	**~14[f],26[a], 36[e], 40.4[d]**	**A1**	**18.0**
R1224yd(Z)	**AMOLEA®1224yd (AGC Chemicals)**	**155.5**	**33.3**	**0.00023[c]**	**0.88[c]**	**20[c]**	**A1**	**14.0**
R365mfc	Solkane®365mfc (Solvay)	186.9	32.7	0	804[a]	8.7 years[a]	A2	40.2
R245fa	Genetron® 245fa (Honeywell)	154.0	36.5	0	858[a]	7.7 years[a]	B1	14.9

HFO

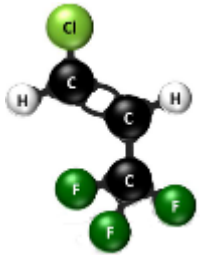


R1336mzz(Z)

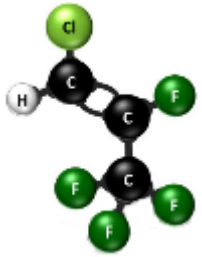


R1234ze(Z)

HCFO



R1233zd(E)



R1224yd(Z)

References:
T_{crit} and p_{crit} (EES F-Chart Software, V10.643, 2019), ODP basis R11=1.0 (UNEP, 2017), GWP_{100} (100-year time horizon, CO_2=1.0), SG: Safety group classification (ASHRAE 34, 2016), [a]Myhre et al. (2013, IPCC 5th assessment report), [b]Fukuda et al. (2014), [c]Tokuhashi et al. (2018), [d]Patten and Wuebbles (2010), [e]Sulbaek Andersen et al. (2018) (3D global model), [f]Andersen et al. (2015)

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Research Gaps in High Temperature Heat Pumps

- **Testing of new environmentally friendly synthetic refrigerants for HTHPs (e.g. HFOs and HCFOs)**
- Application of natural refrigerants, such as hydrocarbons (R600, R601), CO_2 or water
- Extending heat source/sink to higher temperatures
- Improving heat pump efficiency (COP) (e.g. by multi-stage cycles, oil-free compressors)
- Development of temperature-resistant components (e.g. valves, compressors)
- New control strategies for higher temperatures
- Scale-up of functional models to industrial scale

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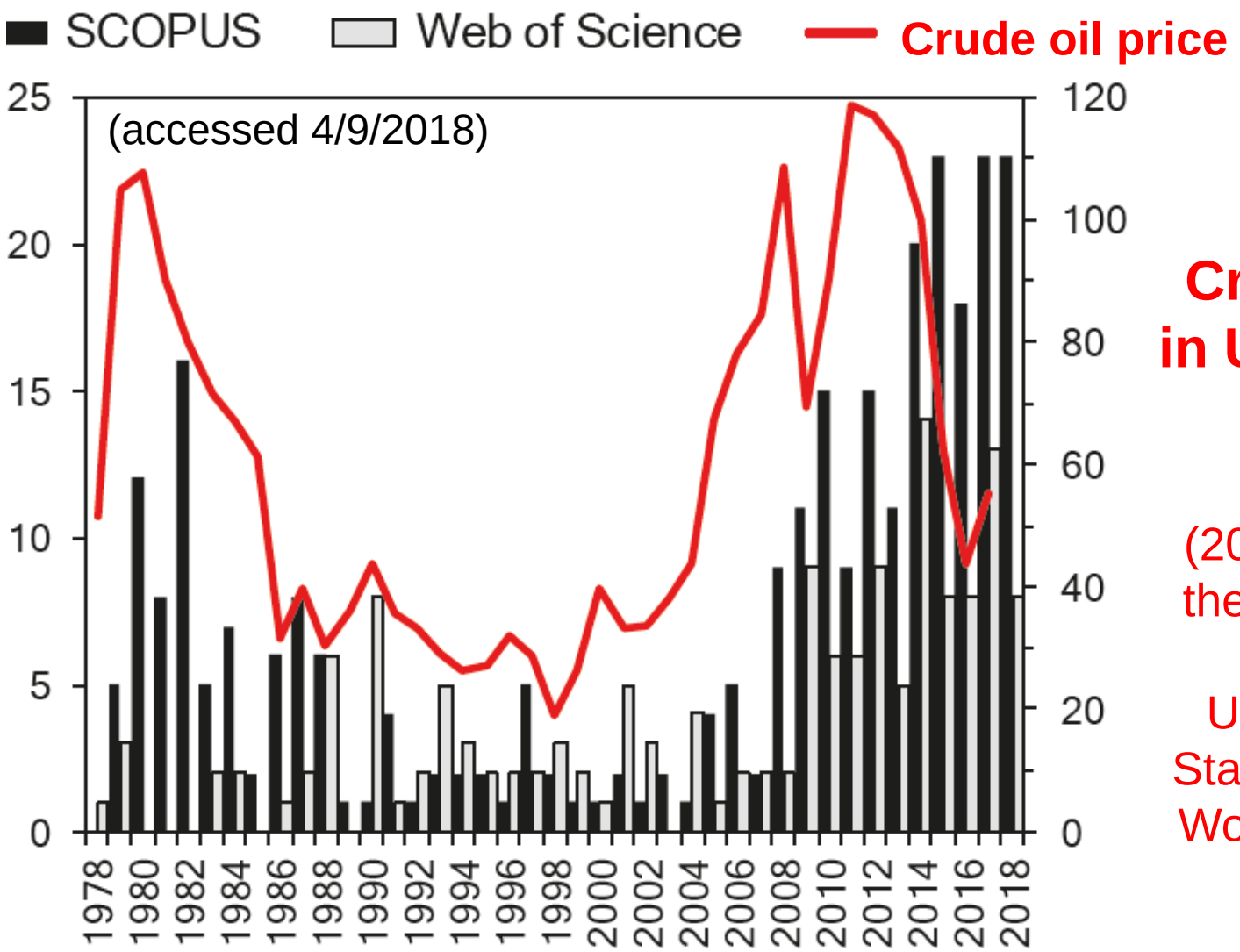
Number of publications – High Temperature Heat Pumps

Number of publications
(with the search term "High Temperature Heat Pump")



Crude oil price in US dollars per barrel

(2017 deflated with the consumer price index for the USA, source: BP Statistical Review of World Energy, June 2018)

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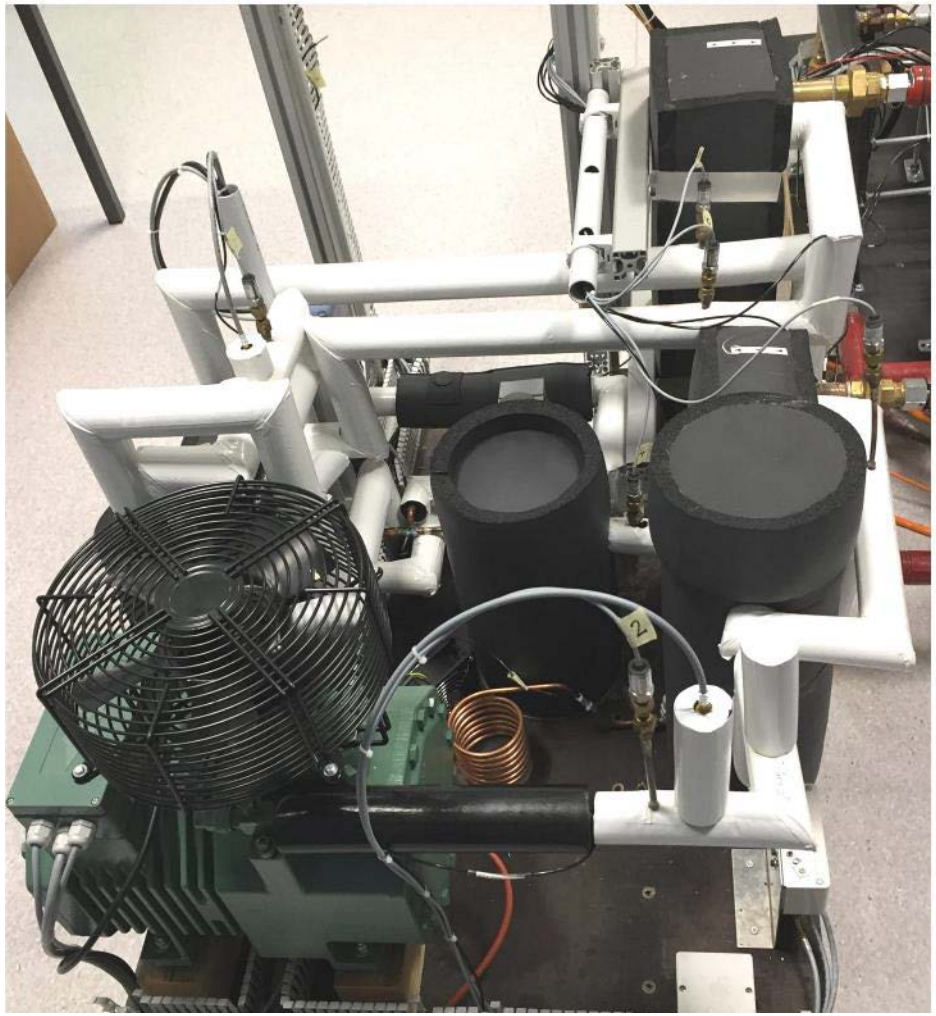
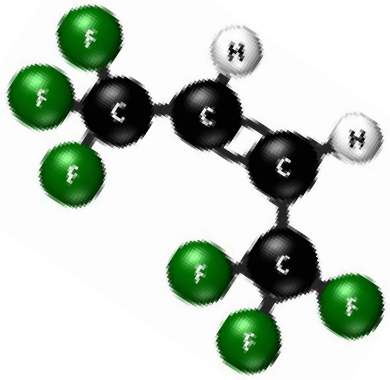
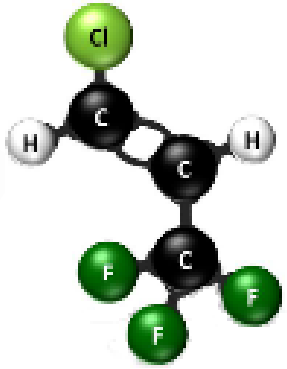
Laboratory HTHP at NTB Buchs with 80 °C to 150 °C supply temperature



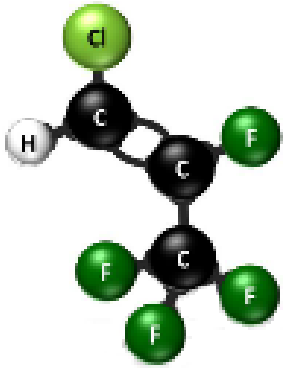
Investigation of different synthetic HFO/HCFO refrigerants



R1336mzz(Z)



R1233zd(E)



R1224yd(Z)

HFO: Hydrofluorolefine, HCFO: Hydrochlorfluorolefine

Properties:

- low GWP (global warming potential)
- zero/low ODP (ozone depletion potential)
- short atm. Lifetime
- Non-flammable
- Non-toxic

Refrigerant	ODP	GWP_{100}	SG
R1336mzz(Z)	0	2	A1
R1233zd(E)	0.00034	1	A1
R1224yd(Z)	0.00023	0.88	A1

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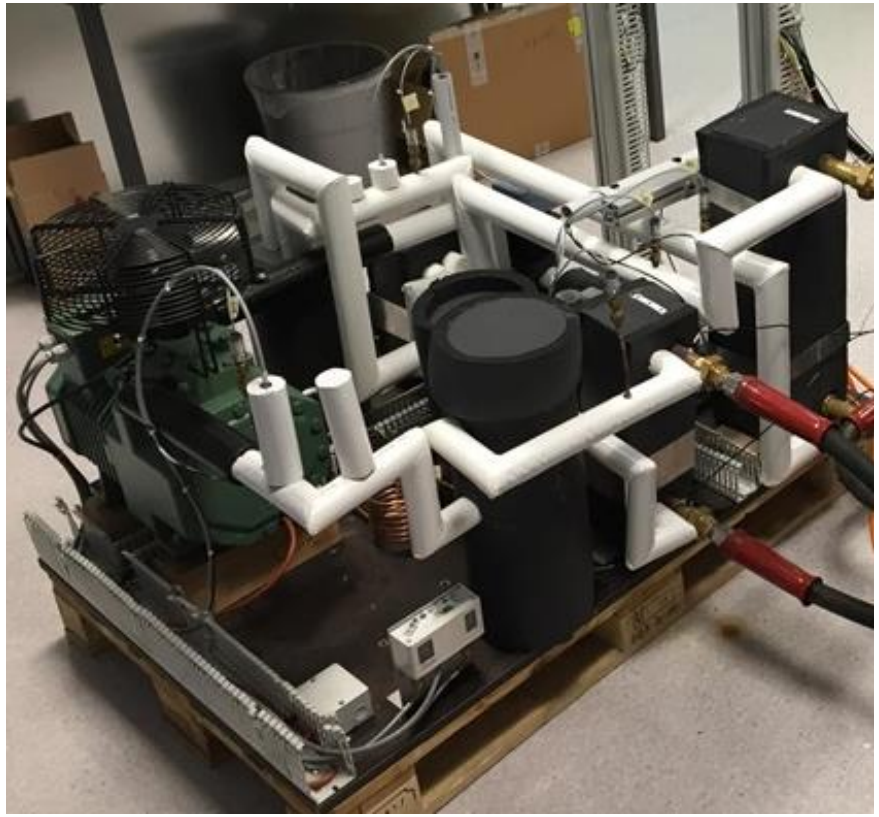
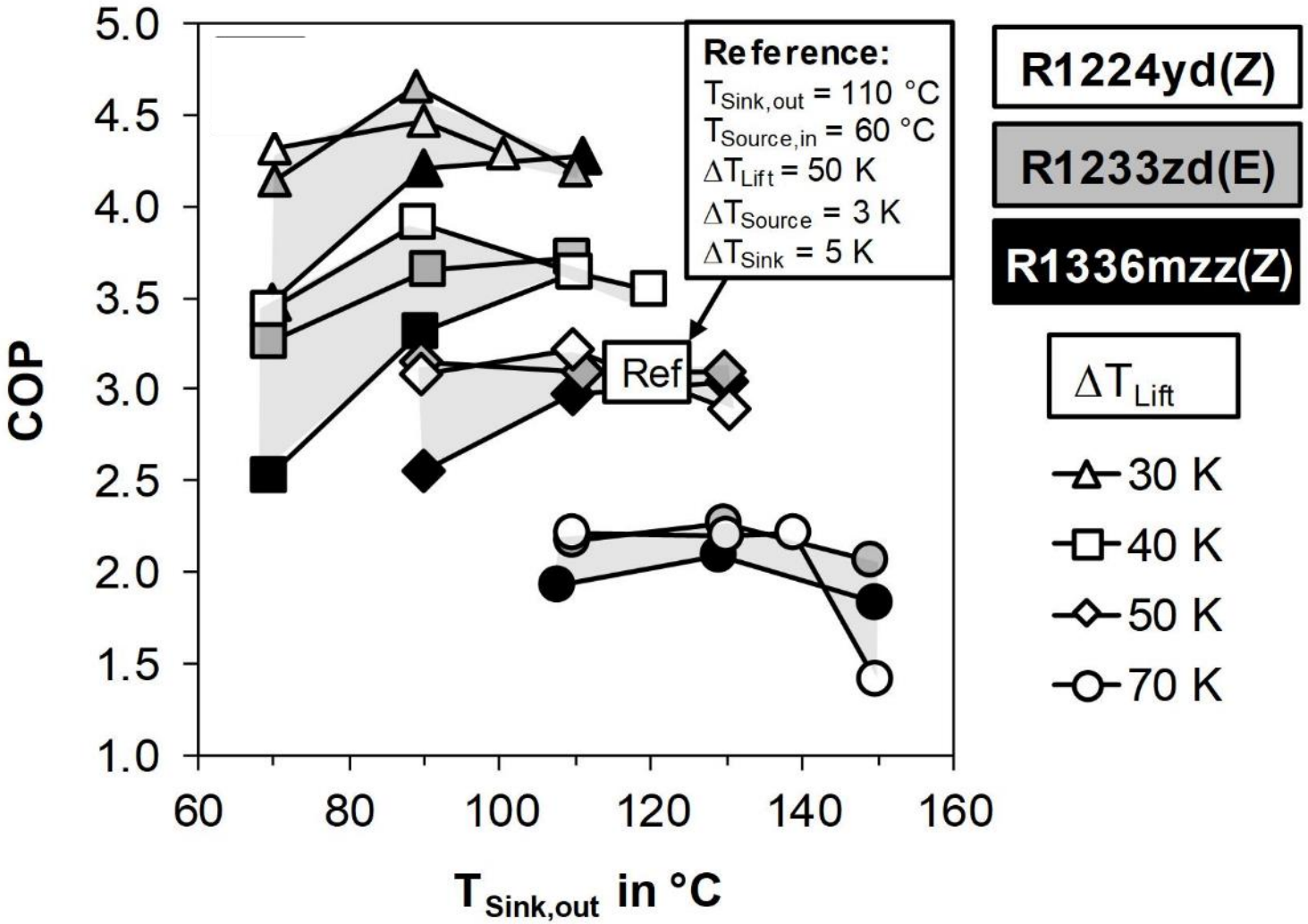
Laboratory scale HTHP at NTB Buchs to research new low GWP HFO and HCFO refrigerants R1224yd(Z), R1233zd(E), and R1366mzz(Z)

Water-Water Heat Pump
1-stage cycle with IHX
piston compressor
5 to 10 kW heating capacity





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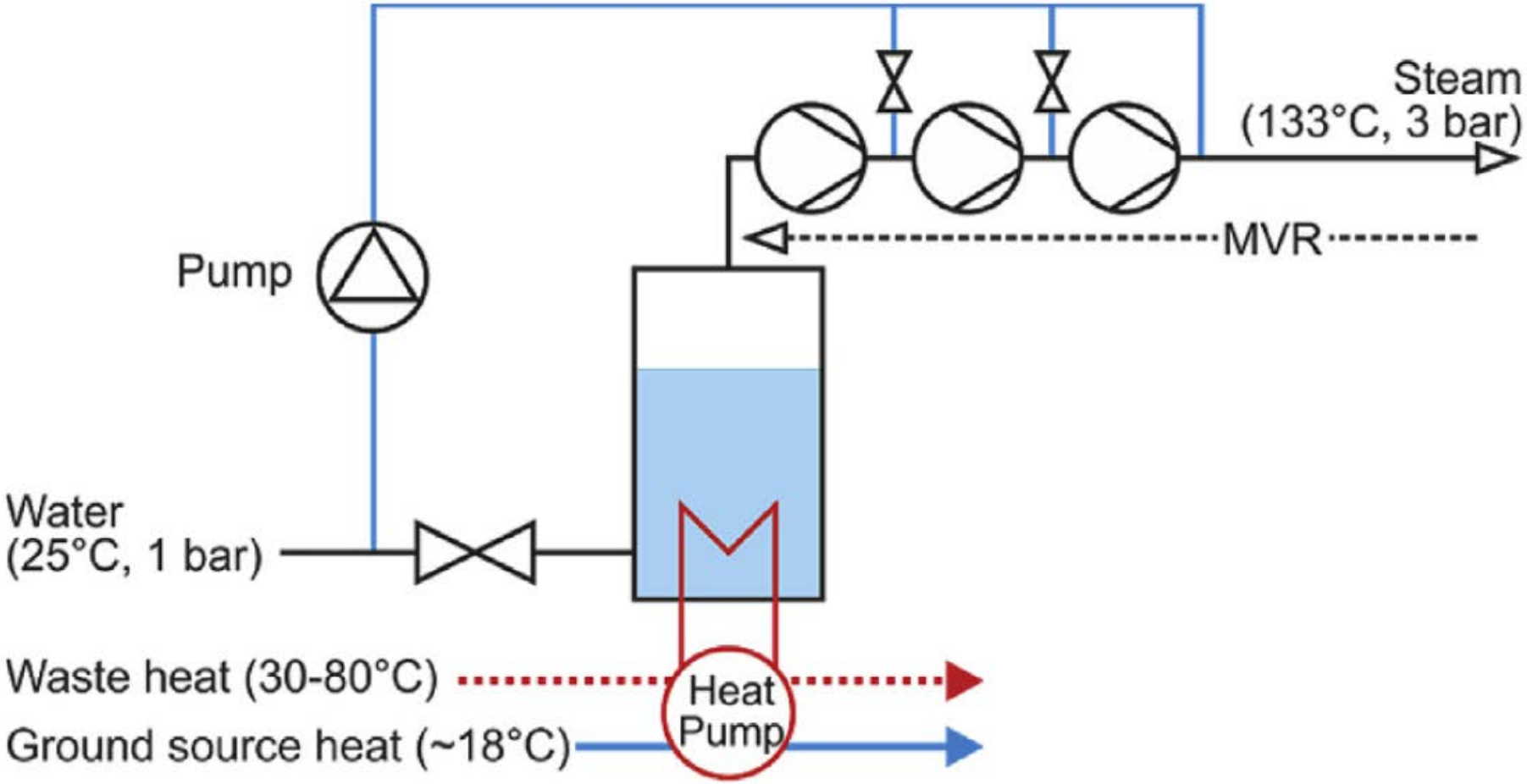
New solutions for steam generation



Bless et al. (2017): Theoretical analysis of steam generation methods - Energy, CO_2 emission, and cost analysis, Energy, 129, 114-121

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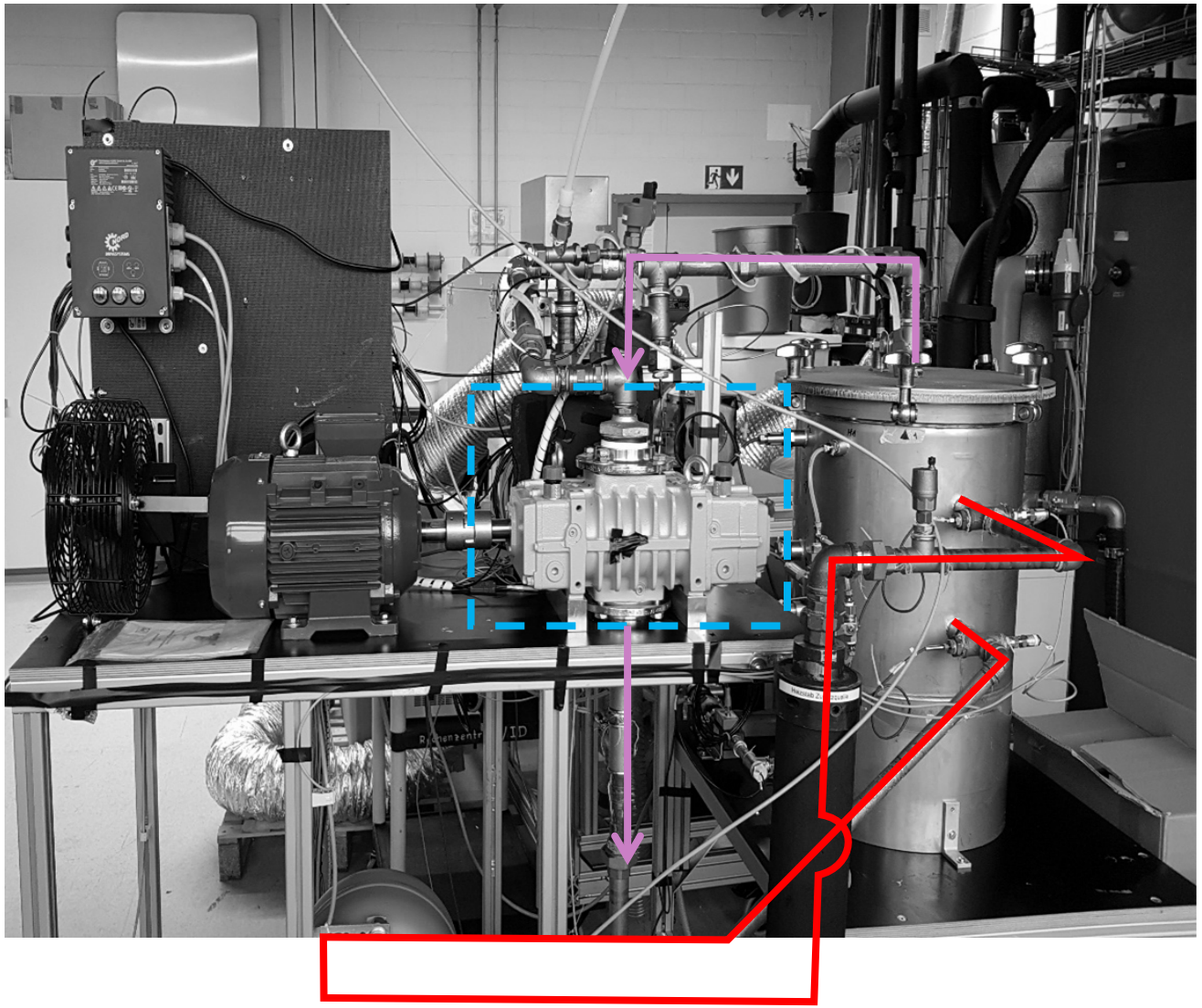
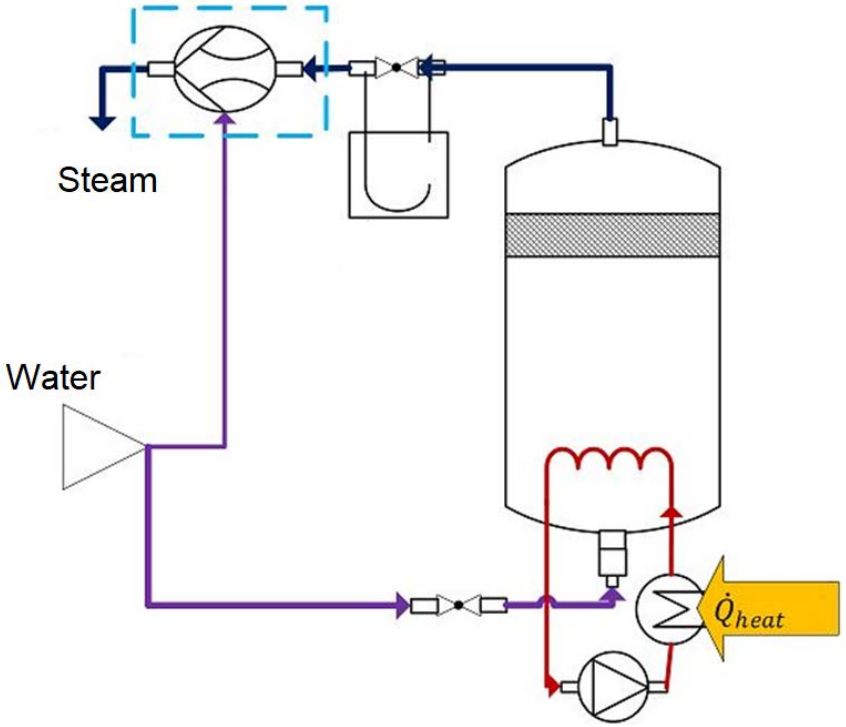
Steam generation from waste heat – lab-scale prototype at NTB



- Heat pump with open water circuit
- Proof of concept
- Produces 34.2 kg/h steam at 115 °C (38.8 kg/h simulated)



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Organization, project partners, country, heat pump cycle, compressor type, refrigerant, heating capacity, and sorted by the heat supply temperature

Organisation, Project partners	Country	Cycle	Compressor	Refrigerant	Source (blue) and supply (red) temperatures [°C]	Heating capacity [kW]	Literature references
					20 40 60 80 100 120 140 160		
Austrian Institute of Technology, Vienna, Chemours, Bitzer		1-stage with IHX	piston	R1336mzz(Z)		12	Helminger et al. (2016)
Austrian Institute of Technology, Chemours, Bitzer, Austria		1-stage	piston	R1336mzz(Z)		12	Fleckl et al. (2015)
NTB University of Applied Sciences of Technology Buchs, SCCER EIP, Switzerland		1-stage with IHX	piston	R1233zd(E) R1224yd(Z) R1336mzz(Z)		3 to 10	Arpagaus et al. (2018, 2019)
PACO, University Lyon, EDF Electricité de France		flash tank	twin screw	R718 (H_2O)		300	Chamoun et al. (2014, 2013, 2012)
Institute of Air Handling and Refrigeration, Dresden, Germany		1-stage	piston	HT 125		12	Noack (2016)
ISTENER Research Group, Universitat Jaume I, Expander Tech (Rank), Spain		1-stage with IHX	scroll	R245fa		11 to 18	Mateu-Royo et al. (2019)
Friedrich-Alexander Universität Erlangen-Nürnberg, Siemens, Germany		1-stage with IHX	piston	LG6		10	Reißner (2015), Reißner et al. (2013)
Alter ECO, EDF Electricité de France		IHX and subcooler	twin scroll	ECO3 (R245fa)		50 to 200	Bobelin et al. (2012), IEA (2014)
Tokyo Electric Power Company, Japan		1-stage	screw	R601 (pentane)		150 to 400	Yamazaki and Kubo (1985)
Austrian Institute of Technology, Edtmayer, Ochsner, Austria		economizer	screw	ÖKO1 (R245fa)		250 to 400	Wilk et al. (2016)

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Organization, project partners, country, heat pump cycle, compressor type, refrigerant, heating capacity, and sorted by the heat supply temperature

Organisation, Project partners	Country	Cycle	Compressor	Refrigerant	Source (blue) and supply (red) temperatures [°C]	Heating capacity [kW]	Literature references
					20 40 60 80 100 120 140 160		
Tianjin University, China		1-stage	scroll	BY-5		16 to 19	Zhang et al. (2017)
Kyushu University, Fukuoka, Japan		1-stage	twin rotary	R1234ze(Z)		1.8	Fukuda et al. (2014)
ECN, SmurfitKappa, IBK, Bronswerk, The Netherlands		IHX and subcooler	piston	R600 (butane)		160	Wemmers et al. (2017)
Korea Institute of Energy Research, Daejeon, Korea		1-stage with steam generation	piston	R245fa/ R718 (H_2O)		20 to 40	Lee et al. (2017)
GREE Electric Appliances, Zhuhai, China		1-stage	scroll	R245fa		6 to 12	Huang et al. (2017)
Norwegian University of Science and Technology, SINTEF		2-stage cascade	piston	R600/R290 (butane/propane)		20 to 30	Bamigbetan et al. (2017)
TU Graz, Austria		1-stage with IHX	piston	R600		20 to 40	Moisi et al. (2017)
Tianjin University, China		1-stage	double scroll	BY-4		44 to 141	Yu et al. (2014)
EDF Electricité de France, Johnson Controls		IHX and economizer	twin screw, centrifugal turbo	R245fa		300 to 500 900 to 1’200	Assaf et al. (2010), IEA (2012, 2014), Peureux et al. (2014)

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Research Status

- **Worldwide high research activity on HTHPs**
- **At least 19 experimental research projects with heat supply temperatures > 100 °C (up to max. 160 °C)**
- Experimental research mainly in **Austria, France, Germany, Norway, the Netherlands, Switzerland, Spain, Japan, Korea and China**
- **Heating capacity: lab scale 12 kW, larger prototypes >100 kW**
- **COPs (at 120°C supply temperature): 5.7 to 6.5 (30 K temperature lift), 2.2 to 2.8 (70 K)**
- Trend towards **natural refrigerants** R600 (butane), R601 (pentane), R744 (CO_2), R718 (H_2O) **and synthetic HFOs with low GWP < 10** (R1336mzz(Z), R1233zd(E), R1224yd(Z), R1234ze(Z))
- Cycles: **mostly 1-stage, optimization with IHX** and/or **Economizer cycle** with intermediate injection into the compressor, **mostly piston compressors** in lab-scale
- **R1336mzz(Z), R1233zd(E) and R1224yd(Z) successfully tested in HTHP at NTB Buchs (drop-in tests)**
- **Integration of an IHX increased COP** (+15 to 47%) and heating capacity **significantly**
- **Operation demonstrated** at **30 to 80°C heat source** and **70 to 150°C heat sink temperatures** (30 to 70 K temperature lifts) for possible application of **waste heat recovery, steam generation or drying**

Application examples in food & steam generation

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Potential applications

HOT WATER

HOT AIR

STEAM

- **Hot water generation for washing and cleaning processes** (e.g. food, meat, bottles, wine tanks, product washing) in combination with cooling generation
- **Hot air generation and air preheating for drying processes** (e.g. starch, pet food) by waste heat recovery
- **Process steam generation** (i.e. low pressure steam) **for the sterilization and pasteurization of food** (e.g. milk, fruit juice) using cooling water or humid exhaust air

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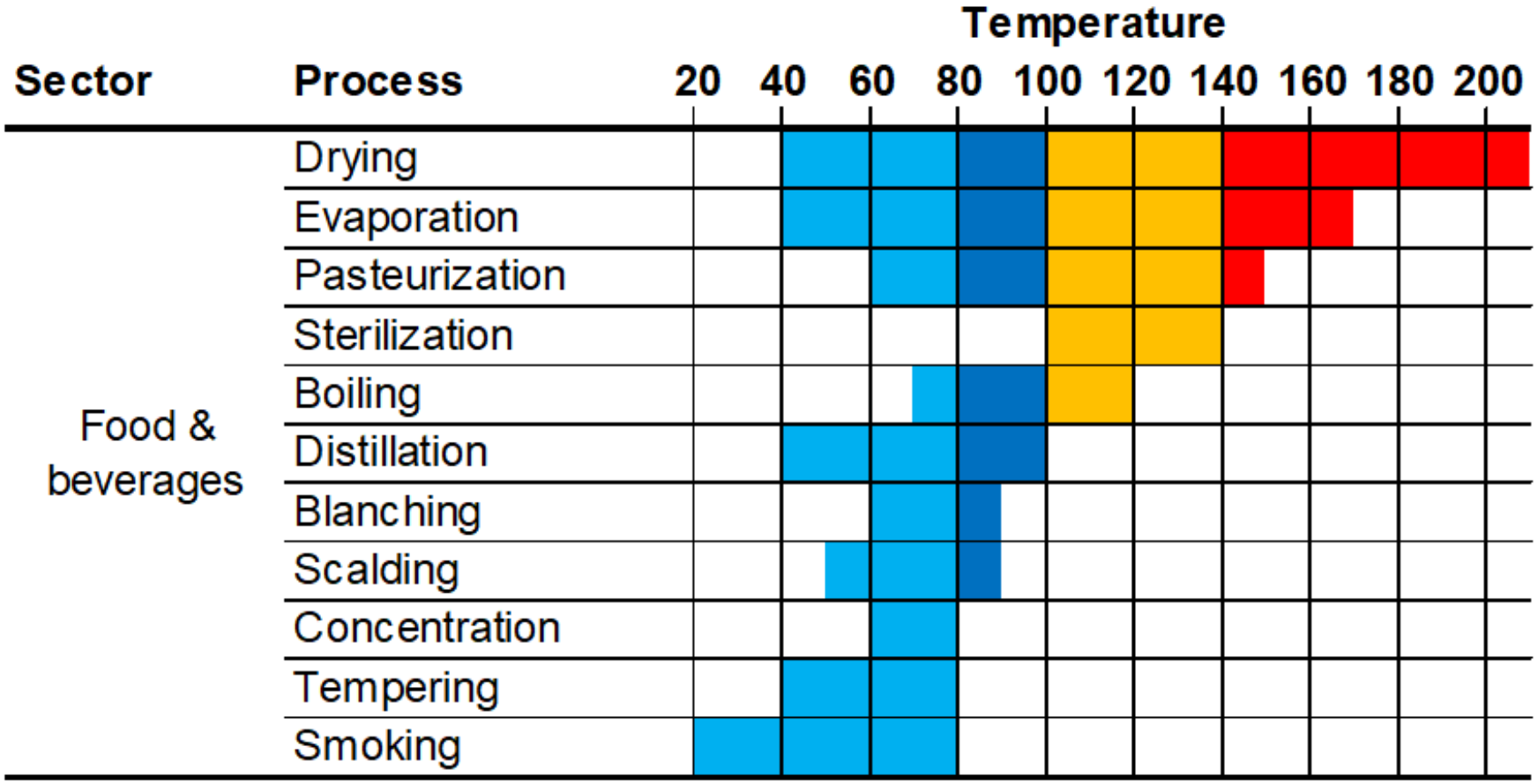
Temperature levels of industrial processes and HP technology readiness



Technology Readiness Level (TRL):

- conventional HP < 80°C, established in industry
- commercial available HP 80 - 100°C, key technology
- prototype status, technology development, HTHP 100 - 140°C
- laboratory research, functional models, proof of concept, VHTHP > 140°C

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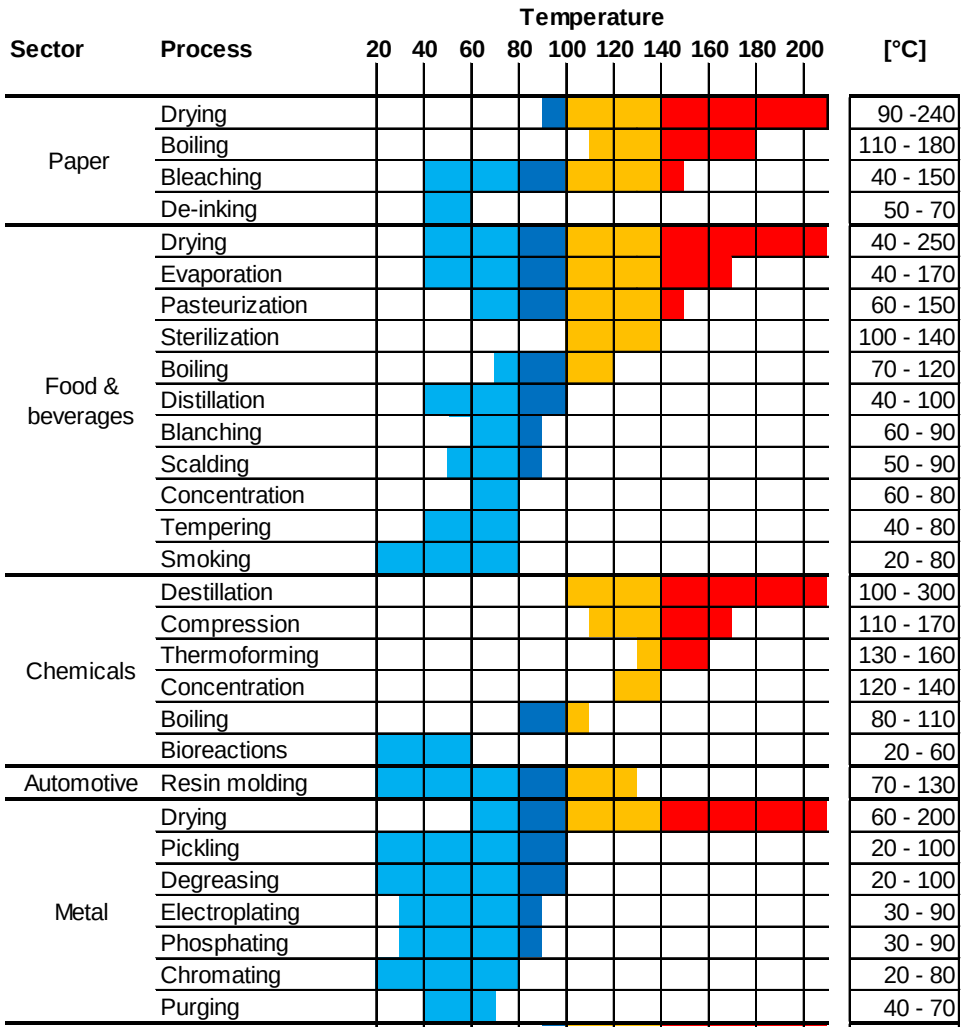
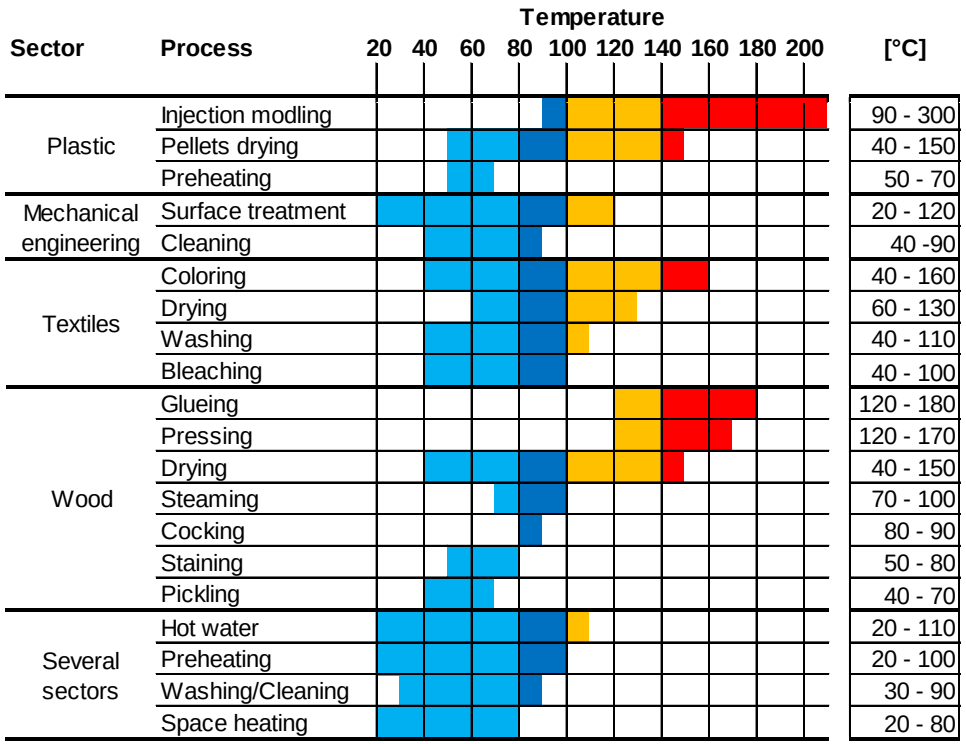
Temperature levels of industrial processes and HP technology readiness





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- prototype status, technology development, HTHP 100 - 140°C
- laboratory research, functional models, proof of concept, VHTHP > 140°C

Data sources: Brunner et al. (2007), Hartl et al. (2015), IEA (2014), Kalogirou (2003), Lambauer et al. (2012), Lauterbach et al. (2012), Noack (2016), Ochsner (2015), Rieberer et al. (2015), Watanabe (2013), Weiss (2007, 2005), Wolf et al. (2014)

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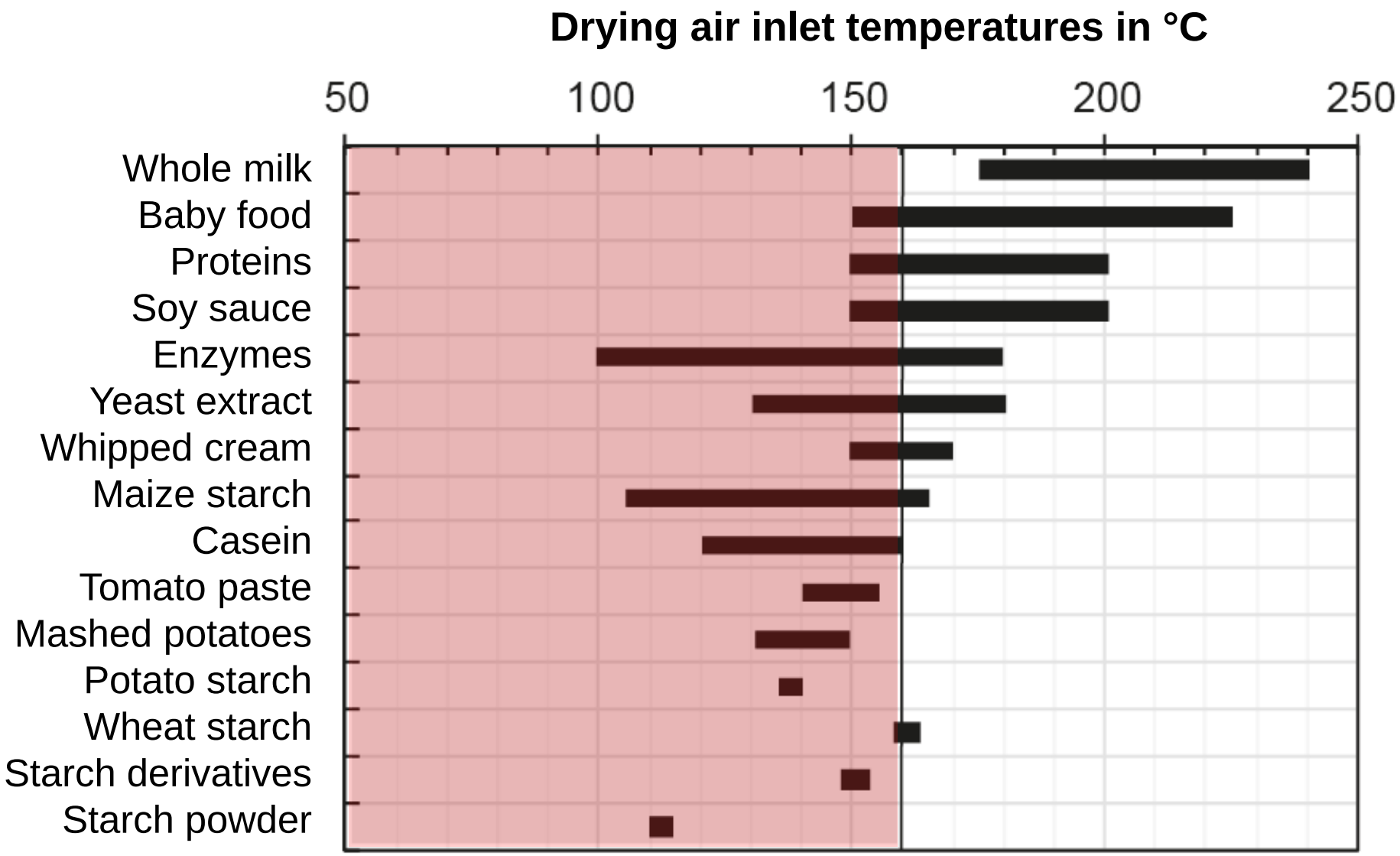
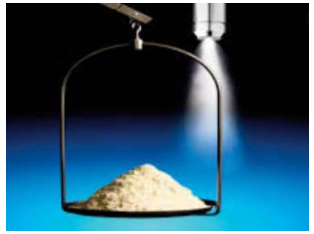
Drying temperatures of various foodstuffs



Food and beverage industry

- Hot water and steam for **sterilization of food and beverages**
- Process heat for **concentration and pasteurization of milk and juices**
- Hot water and steam for **washing and sterilizing bottles and wine tanks during bottling** processes
- Steam and hot water for **slaughterhouse cleaning**
- Process heat for **pasteurization and hot water in cheese factories**

Drying processes (air heating)



- **Brick drying:** Air preheating to 120 °C by means of moist exhaust air (70 °C, 50% r.h.)
- **Wood drying:** Air heating to 120 to 150 °C with moist exhaust air
- **Starch drying:** Air preheating for steam generation 160 °C
- **Drying of animal fodder:** Low pressure steam for chamber dryer
- **Spray drying:** Air preheating for milk powder production
- **Paper drying:** Low-pressure steam 130 °C using cooling water (60°C) or humid exhaust air (76 °C, 56 % r.h.) as heat source

More application examples

- **District heating networks:** Hot water production up to 120 °C
- **Hospitals:** Steam 125 °C for autoclaves, sterilization and laundry drying
- **PET bottle industry:** Process heat between 100 and 150 °C for injection molding of plastic preforms
- **Sugar industry:** Process heat between 80 and 150 °C for the processing of sugar beets, steam generation at 138 °C for the production of 90 °C feed water

More application examples

- **Breweries:** Process heat of around 100 °C for the brewing process (e.g. mashing, lautering, wort boiling)
- **Milk processing:** Milk pasteurization (HT 100 to 120 °C), sterilization (115 to 135 °C) and UHT (135 to 150 °C), spray drying of milk powder (preheating the drying air to 120 to 150 °C)
- **Chemical industry:** Steam 120 °C for alcohol distillation using the waste heat of the cooling tower or the condensation heat of the distillation column (65 °C)
- **Wellness sauna:** CO_2 heat pumps for different temperature levels up to 120 °C

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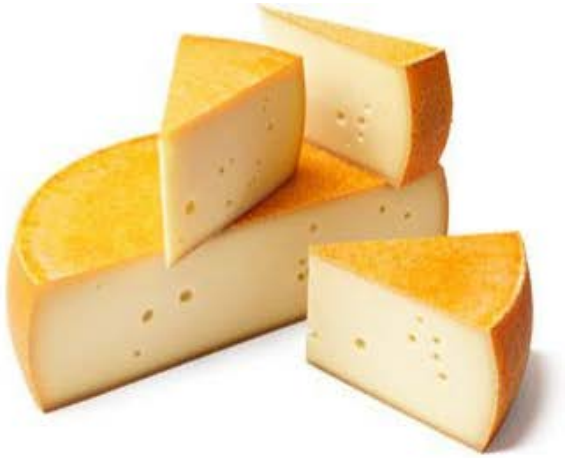
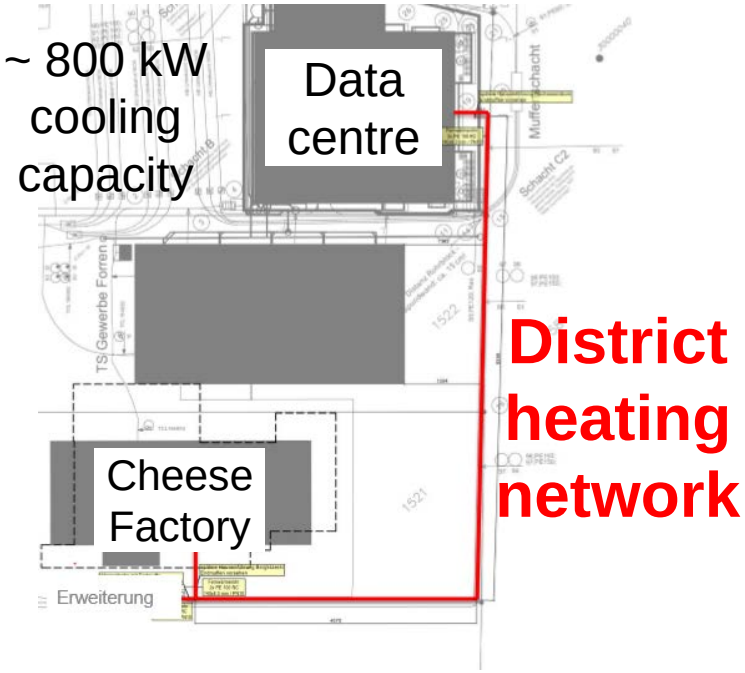
Cheese Factory in Gais Appenzell



Data Centre

Waste heat from server rooms 16 to 20 °C



Cheese Factory

- Energy demand ~1’800 MWh/a
- ~10 Mio. liters of milk per year
- ~300 tons of cheese per year

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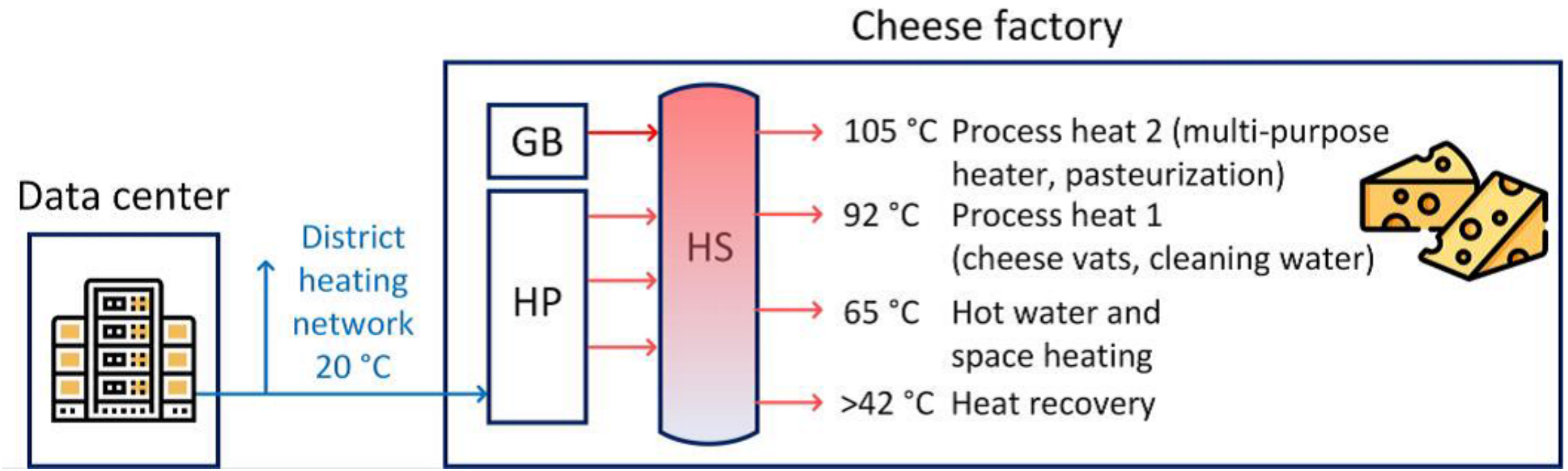
Cheese Factory in Gais Appenzell



(GB: gas boiler, HP: heat pump, HS: stratified hot water storage tank)

- Waste heat from the server cooling of the neighboring data center is fed into a district heating network at approx. 20 °C.
- The cheese factory uses this waste heat as heat source in a high temperature heat pump to generate process heat for the cheese production.

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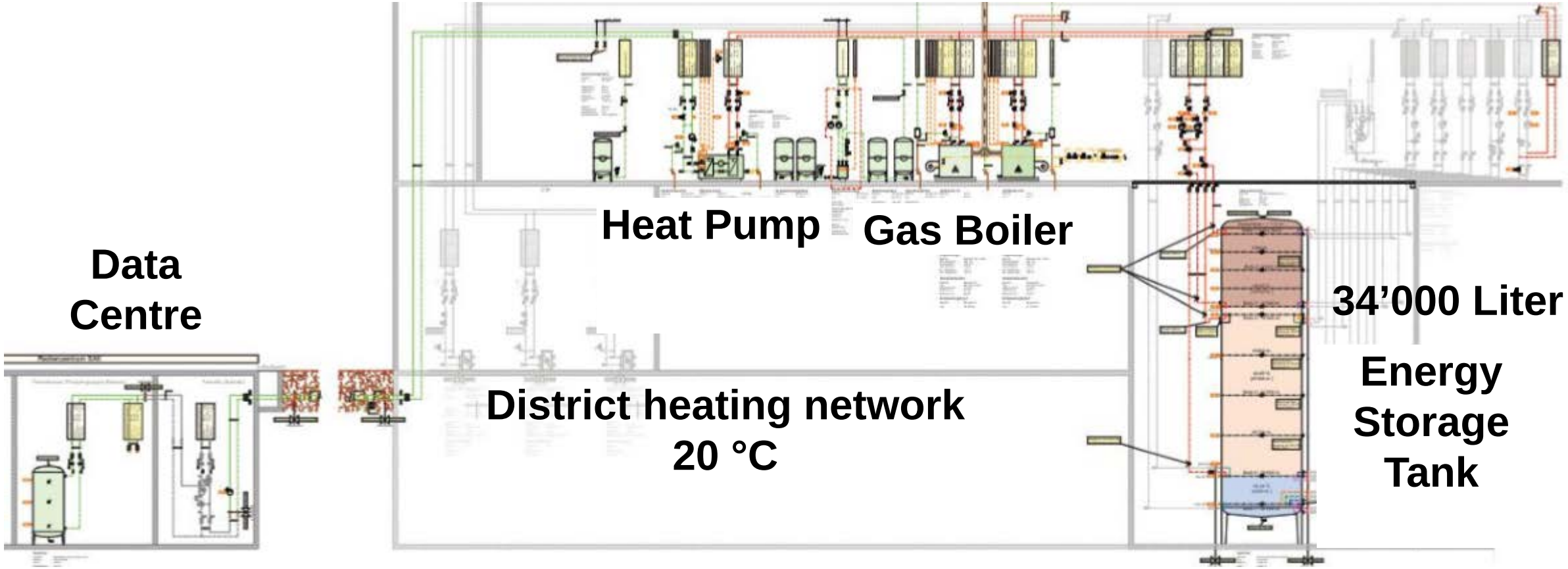
Cheese Factory in Gais Appenzell



Source: Amstein + Walthert

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Cheese Factory in Gais Appenzell

- **IWWHS 570 ER6c2**
- **~520kW**
- 2-stage screw compressor
- **Economizer cycle**
  - Refrigerant mass flow ↑
  - Discharge temp. ↓
  - Subcooling ↑ (COP ↑)
- **R1234ze(E)**
  (130 kg, safety group: A2L, mildly flammable, special measures for fire protection and escape routes)
- **2020/21 first operation**
  (using waste heat from data centre)

Heat Pumping Technologies MAGAZINE
IEA HPT
VOL.37 NO 2/2019

Performance data (W18-14/W82-92)

Part load (%)	100	75	50
Effective part load (%)	100	81	62
Condenser heating capacity (kW)	**520**	**419**	**321**
Condenser water flow rate (m^3/h)	44.7	36.0	27.6
Temperature difference condenser (K)	10.0	10.0	10.0
Evaporator capacity (kW)	338	264	195
Evaporator water flow rate (m^3/h)	82.7	82.7	82.7
Temperature difference evaporator (K)	3.5	2.7	2.0
Compressor power (kW)	182	155	126
COP_H (-)	**2.85**	**2.70**	**2.55**

Chocolate Factory in Flawil

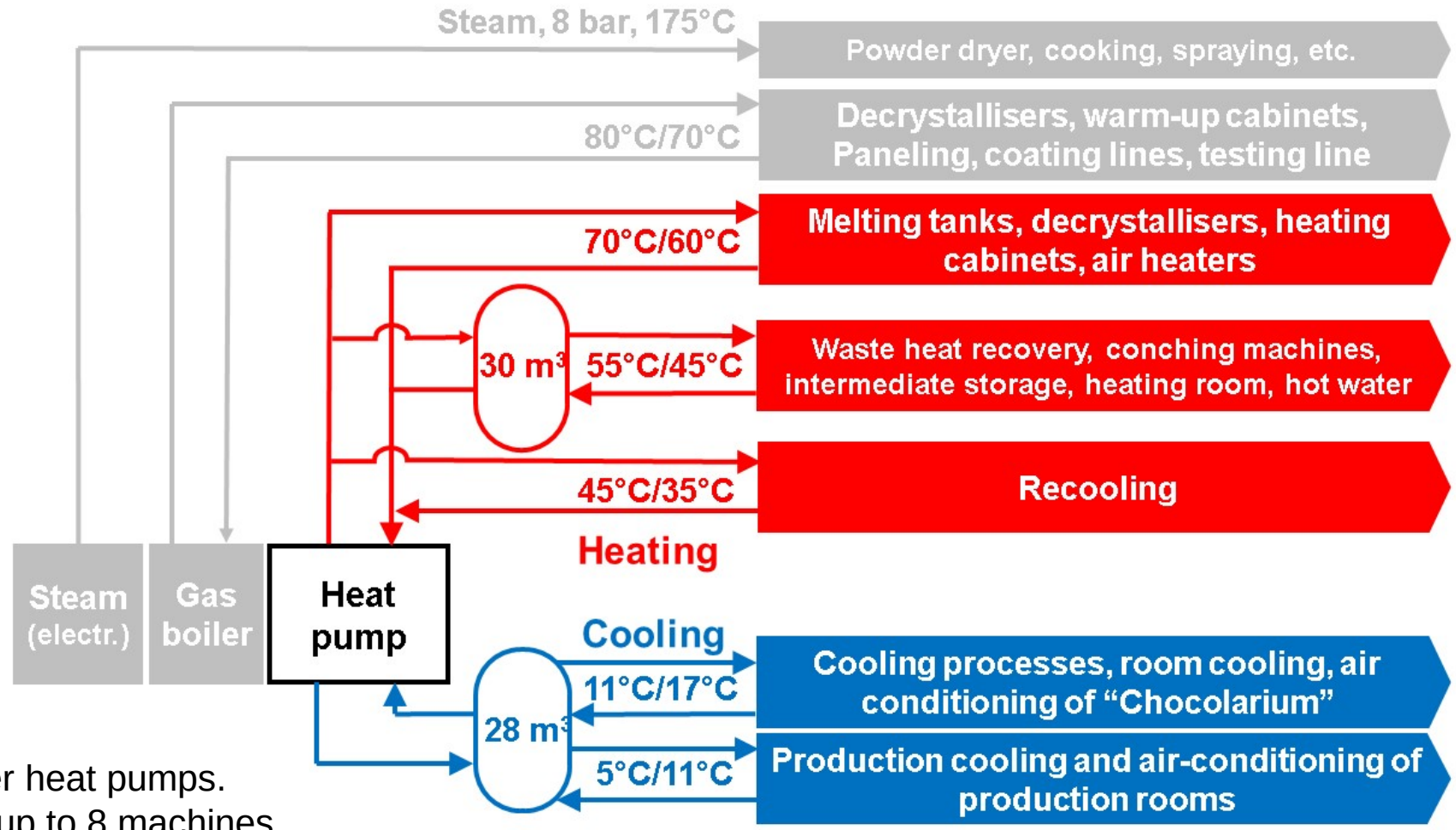
HP manufacturer: CTA AG
Contractor: Seiz AG
Consultant: Carnotech AG

Temperature range from 5 to 70 °C
Space for 8 heat pumps à 220 kW
Application: Cooling and heating of chocolate conching machines
Savings fossil fuels = 2'590 MWh
Savings CO_2 emissions = 30% (510 t/a)

	Cooling	Heating
Cooling capacity	222.6 kW	183.7 kW
Electrical power	70.4 kW	96.8 kW
Heat source in/out	5/11°C	11/17°C
Heating capacity	289.8 kW	276.2 kW
COP	4.12	2.85
Hot water in/out	35/45°C	**60/70°C**
Refrigerant	R-1234ze	**R-1234ze**
Piston compressors	4	4
No. of cooling cycles	2	2

Sources: www.maestrani-schokolade.ch, www.cta.ch

Chocolate Factory in Flawil



The three tailor-made water/water heat pumps.
The machine room offers space for up to 8 machines with a final cooling capacity of 2 MW.

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GVS Schaffhausen, Landi – Beverages

Savings:
CO_2-emissions (-40%)
~26’000 Liter oil/year (~1 barrel/day)

Heat sink: 80 to 95 ºC
- **process water for disinfection of beverage filling plants and wine tanks**
- space heating of storage rooms
- district heating of production site

Heat source: 37 ºC
- waste heat from refrigeration (cooling of storage rooms)

Heat pump type:	**ISWHS 60 ER3**
Heating capacity:	63 kW
Cooling capacity:	48 kW
Compressor:	Screw, ÖKO 1 (R245fa)
COP Heating:	4,2
EER Cooling:	3,2
Year of installation:	2017

Source: Ochsner, Ennovatis Schweiz AG

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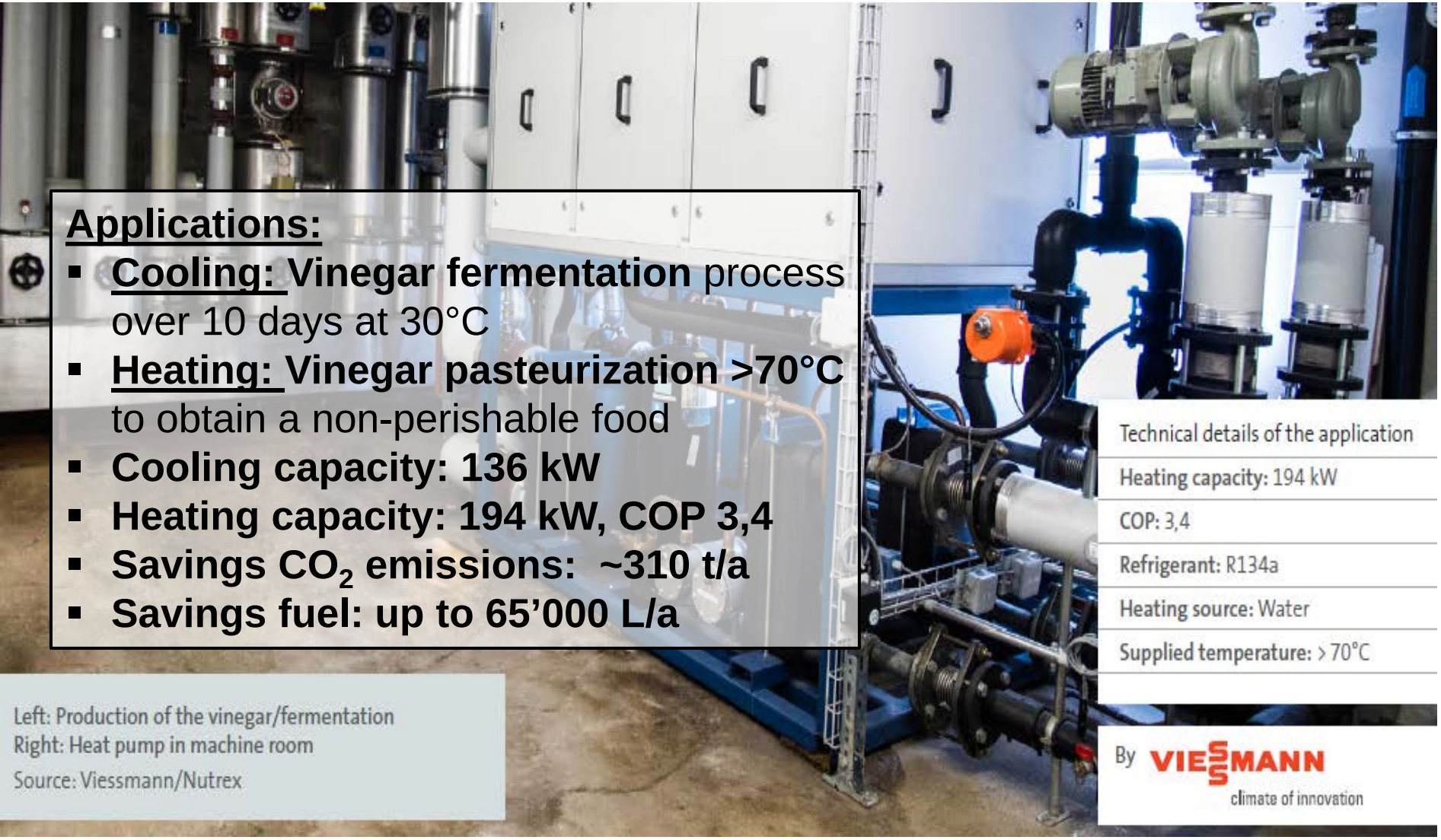
Nutrex – Vinegar fermentation and pasteurization



Applications:

- **Cooling: Vinegar fermentation** process over 10 days at 30°C
- **Heating: Vinegar pasteurization >70°C** to obtain a non-perishable food
- **Cooling capacity: 136 kW**
- **Heating capacity: 194 kW, COP 3,4**
- **Savings CO_2 emissions: ~310 t/a**
- **Savings fuel: up to 65'000 L/a**

Technical details of the application

Heating capacity: 194 kW
COP: 3,4
Refrigerant: R134a
Heating source: Water
Supplied temperature: > 70°C

By VIESSMANN climate of innovation

Left: Production of the vinegar/fermentation
Right: Heat pump in machine room
Source: Viessmann/Nutrex

Source: EHPA (2017): Large scale heat pumps in Europe

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Slaughterhouse Zurich – Meat Production

Process applied	**Hot water for cleaning processes up to 90°C and space heating**
Location	Zurich (in the middle of the city, historical building)
Year of installation	2011
HP manufacturer	Thermea, Germany
Contractor	ewz Energiedienstleistungen
Consultant	City of Zurich
Refrigerant	**CO_2 (R744)**
Compressor	Screw
Heating/cooling capacity (kW)	800/564
Heat source	**Waste heat from refrigeration processes** (closed water loop with storage tank) and **waste heat from compressed air generation**
Heat source (°C) in/out	20/14
Heat sink (°C) in/out	**Water, 30/90**
Efficiency (COP)	3.4
Savings CO_2 emissions	30% (510 t/a), saving of 2’590 MWh fossil fuels

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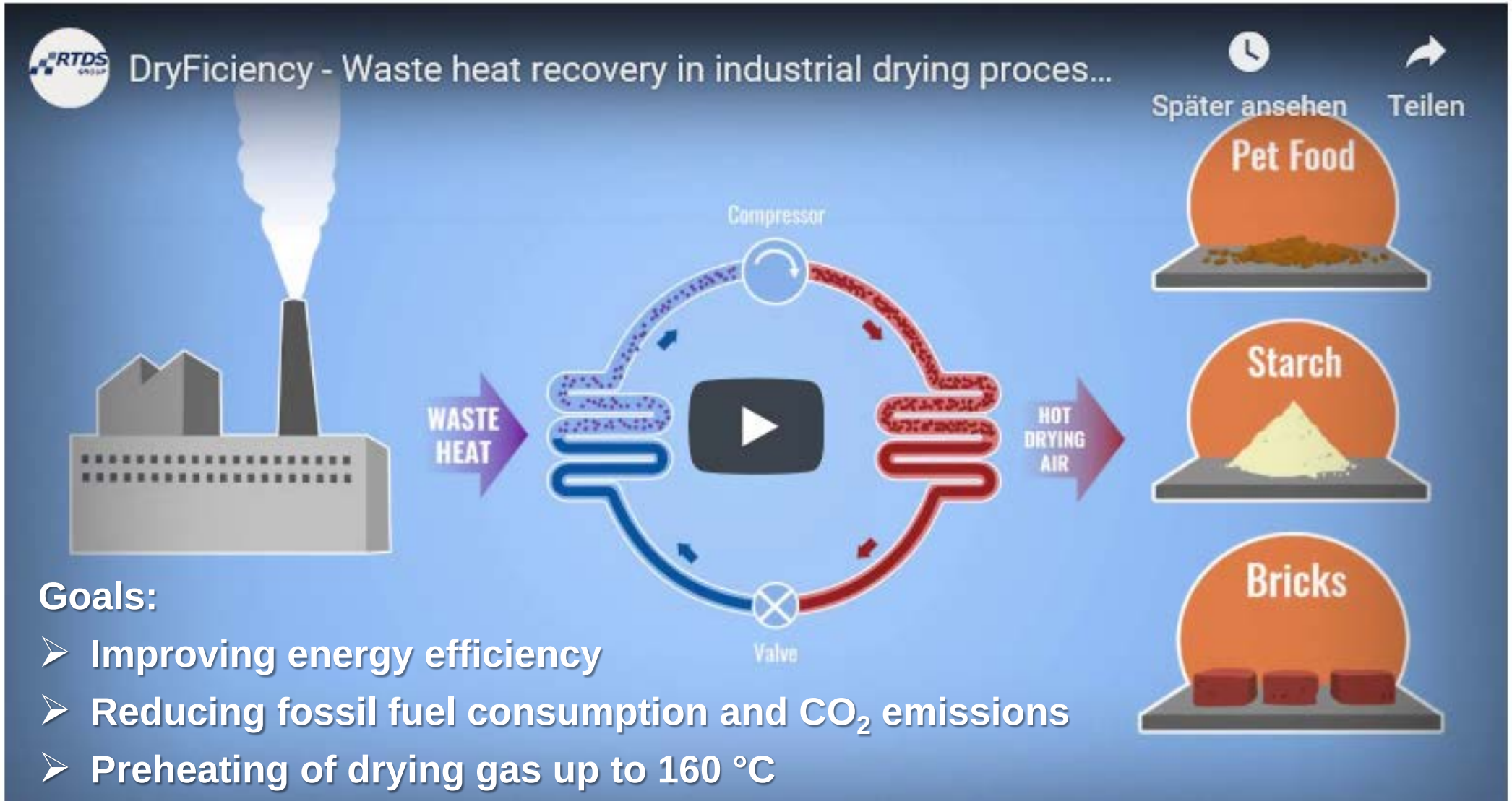
Heat recovery in drying processes



Goals:

- Improving energy efficiency
- Reducing fossil fuel consumption and CO_2 emissions
- Preheating of drying gas up to 160 °C

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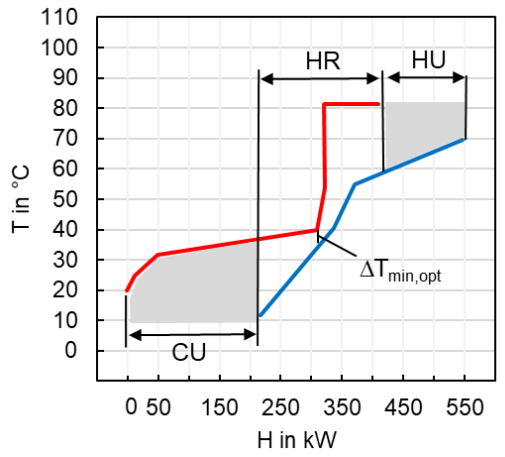
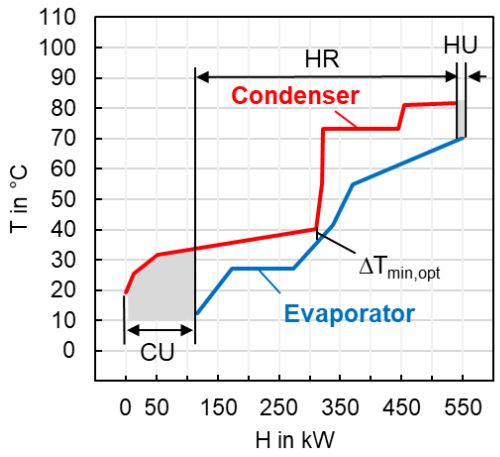
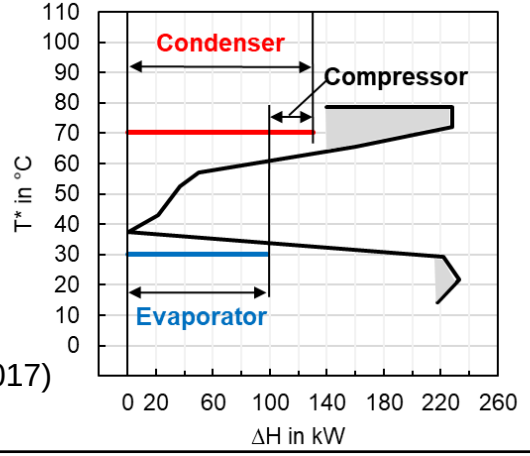
Heat pump integration: questions to be answered

1. Are there **processes with heat demand**?
2. Are there **processes with cooling demand**?
3. What is the required heat **supply temperature**?
4. Are sufficient **heat sources** available for high heat supply temperatures?
5. Is the **heat source** approx. in the same order of magnitude as the **heat demand**?
6. Is the heat source available **at about the same time** as the heat sink?
7. What is the **heat recovery potential**?
8. What is the **operation profile** of the heat pump (part-load, fluctuations)?

Pinch Analysis Case Study Food Industry - Candy Production







HR: heat recovery
CU: cold utility
HU: hot utility

Data from Olsen et al. (2017)

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Summary

- **Application potential for industrial heat pumps is large:** hot water, hot air, and process steam
- **Numerous industrial heat pumps from various manufacturers are available on the market:** supply temperatures > 90°C (some > 120°C, up to max. 165°C), rotational heat pump, HTHP on a large scale (MW capacity range)
- **COP (coefficient of performance) of about 4.0 at 50 K temperature lift**, 45% Carnot efficiency, heating and cooling application $COP_{H+K} = 2 \times COP_H - 1$
- **Different circuits:** mostly 1-stage, optimizations with IHX and Economizer with intermediate injection into the compressor, parallel connection of compressors, cascade (R134a/R245fa), compressors: screws, 2-stage turbos, reciprocating piston (parallel)
- **Heat pump integration** varies greatly from case to case: usually with storage tank and often bivalent (e.g. HP for base load, gas boiler for peak coverage and redundancy)
- **High research activity worldwide:** Supply temperatures > 100 °C, mainly DE, AT, CH, FR, NO, NL, JP, KR, and CN
- **Refrigerant development HFOs or natural?** Trend towards natural refrigerants R600 (butane), R601 (pentane), R744 (CO_2), R718 (H_2O) and synthetic HFOs / HCFOs with low GWP, like R1336mzz(Z), R1233zd(E), R1224yd(Z)

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Acknowledgements

This research project is part of the

Swiss Competence Center for Energy Research SCCER EIP

of the Swiss Innovation Agency Innosuisse.

We would like to thank **Innosuisse** for their support.

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Innosuisse – Swiss Innovation Agency

Bundesamt für Energie (BFE)
Vertragsnummer: SI/501782-01
Project: HTWP-Annex 48 – Beitrag über HTWP zum IEA TCP HPT Annex 48

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Thank you for your attention

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