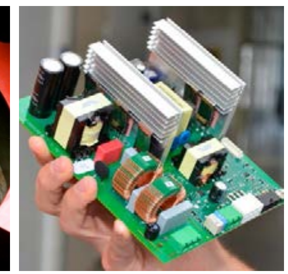
International Workshop on High Temperature Heat Pumps, Sept. 9, 2017, Kopenhagen

Review on High Temperature Heat Pumps – Market Overview and Research Status



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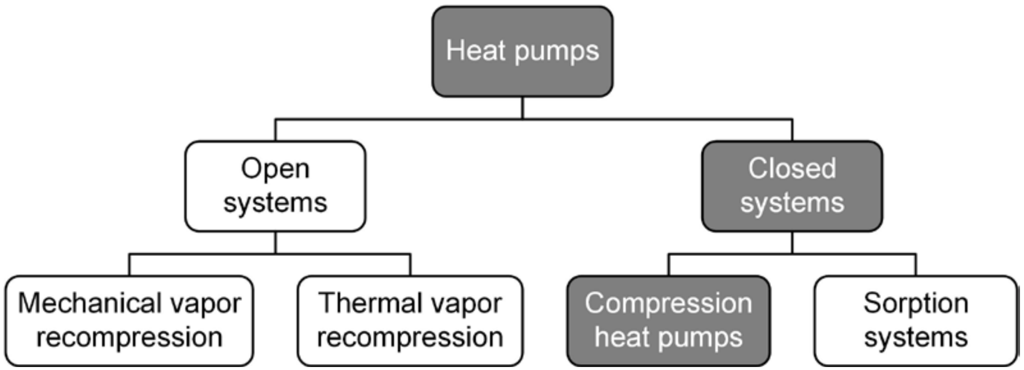
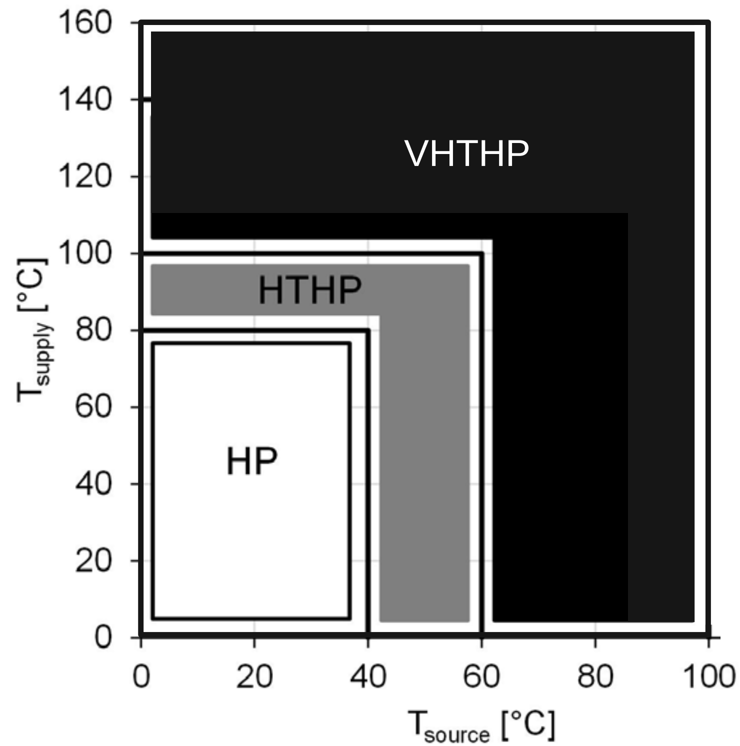
Outline

1. **Market overview of commercially available industrial HTHP systems**
   - Cycles, refrigerants, application limits, efficiencies
2. **Research status**
   - Screening of research activity
   - Experimental and theoretical studies, cycles, refrigerants, supply temperatures, operating ranges
3. **Refrigerants**
   - Selection criteria, properties, GWP, price, efficiency, safety
4. **Conclusions**

Classification of heat pumps (focus on compression heat pumps) Development of temperature levels



adapted from Nellissen and Wolf (2015)

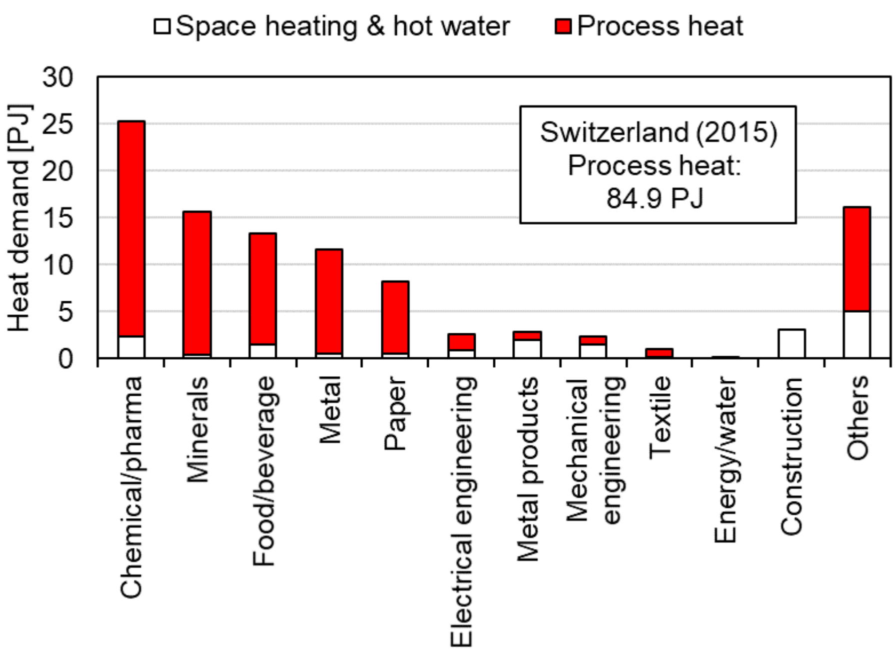


VHTHP: very high temperature heat pump
HTHP: high temperature heat pump
HP: conventional heat pump

adapted from
Bobelin et al. (2012), IEA (2014), Jakobs and Laue (2015), Peureux et al. (2012, 2014)

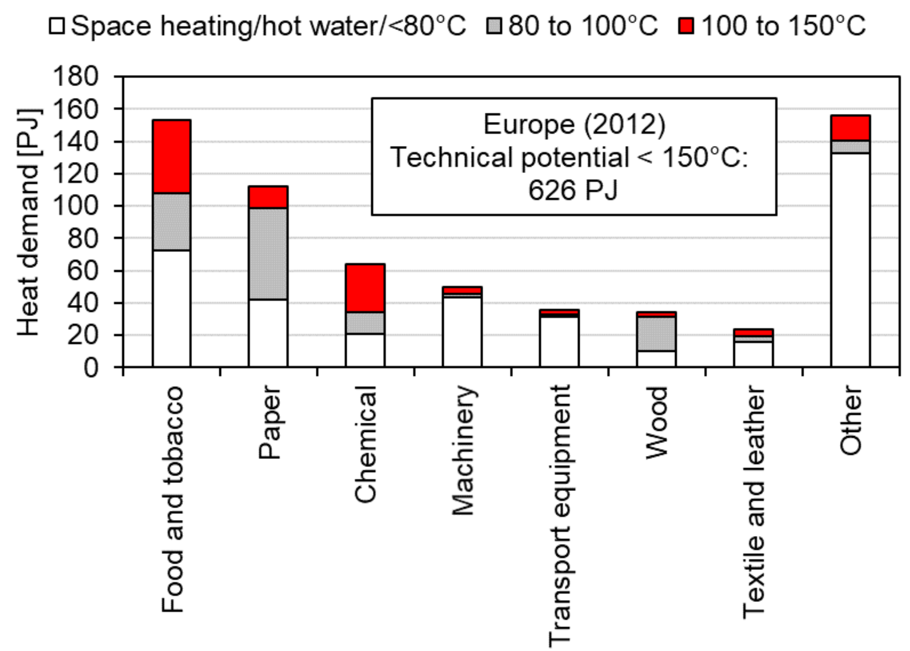
Potential for high temperture heat pumps – Process heat in industry

Theoretical potential for HTHPs in Switzerland



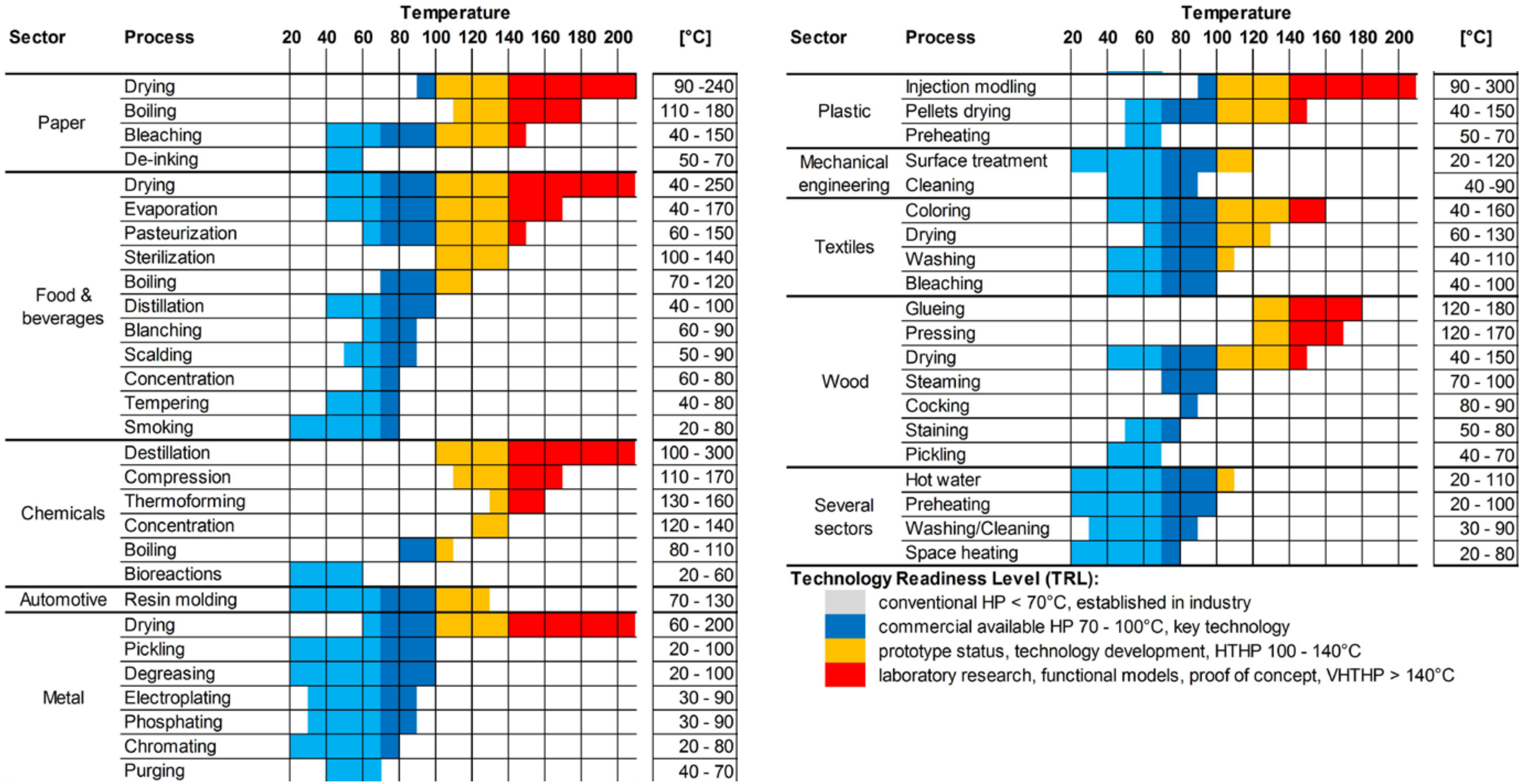
Data from BFE (2016), Pulfer and Spirig (2015)

Technical potential of process heat in Europe accessible with industrial heat pumps



Based on Eurostat data from 2012 of 33 countries, Nellissen and Wolf (2015)

Overview of processes in different industrial sectors
Temperature levels and technology readiness level



<u>Data sources:</u> *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)*

Selection of industrial HTHPs with supply temperatures > 90°C

Manufacturer	Product	Refrigerant	Max. supply temp.	Heating capacity	Compressor type
Kobelco (Steam Grow Heat Pump)	SGH 165 SGH 120 HEM-HR90, HEM-90A	R134a/R245fa R245fa R1r34a/R245fa	165°C 120°C 90°C	70 – 660 kW 70 – 370 kW 70 – 230 kW	Double screw
Vicking Heating Engines AS	HeatBooster	R1336mzz(Z) R245fa	150°C	28 – 188 kW	Piston
Ochsner	IWWDS IWDS 330 ER3 IWHS ER3	R134a/ÖKO1 (R245fa)	130°C 105°C 95°C	170 – 750 kW (twin unit 1.5 MW) 100 – 350 kW 190 – 750 kW	Screw
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
Dürr Thermea	thermeco2	R744 (CO_2)	110°C	45 – 2'200 kW	Piston
Combitherm	Sonderanfertigung	R245fa	100°C	20 – 300 kW	Piston
Friotherm	Unitop 22 Unitop 50	R1234ze(E) R134a	95°C 90°C	0.6 – 3.6 MW 9 – 20 MW	Turbo (2-stage)
Star Refrigeration	Neatpump	R717 (NH_3)	90°C	0.35 – 15 MW	Screw
GEA Refrigeration	GEA Grasso FX P 63 bar	R717 (NH_3)	90°C	2 – 4.5 MW	Double screw
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 Screw Turbo
Mitsubishi	ETW-L	R134a	90°C	340 – 600 kW	Turbo (2-stage)
Viessmann	Vitocal 350-HT Pro	R1234ze(E)	90°C	148 – 223 kW	Piston (2-3 stages)

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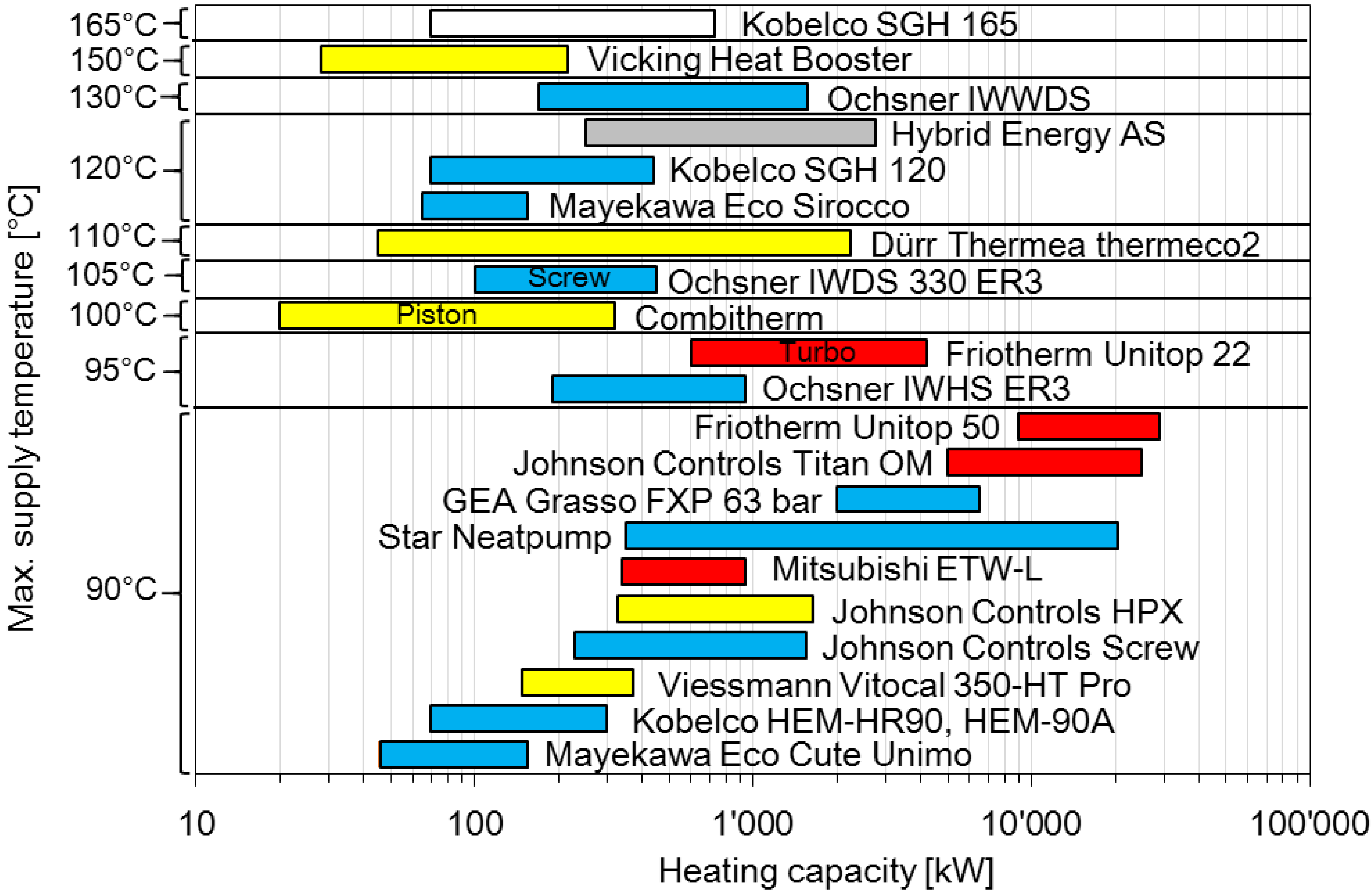
Industrial HTHPs –
Heating capacities vs. achievable supply temperatures



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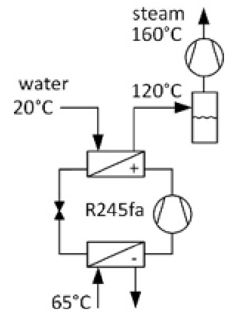
Commercial HTHPs – cycles, COPs and pictures

Kobelco SGH 120 / 165

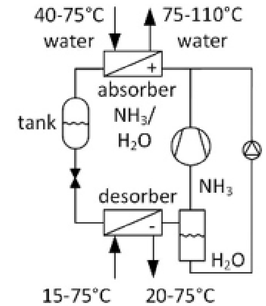
(IEA, 2014a; Kaida et al., 2015; Kuromaki, 2012; Watanabe, 2013)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
65/120 (55)	3.5

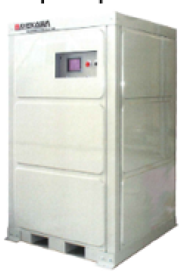
Hybrid Heat Pump

(Jensen et al., 2015a, 2015b)

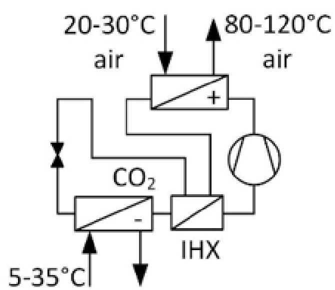


T_{LT}/T_{HT} (ΔT_{Lift})	COP
20/95 (75)	2.4
40/100 (60)	4.5

Mayekawa transcritical CO_2 heat pump Eco Sirocco



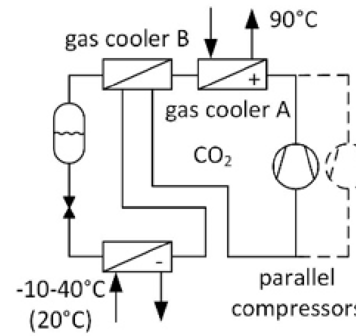
(IEA, 2014a; Mayekawa, 2010; Watanabe, 2013)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
20/100 Luft (80)	3.4
25/120 H_2O (95)	2.9

Thermeco$_2$ HHR1000 with 6 piston compressors, up to 1100 kW

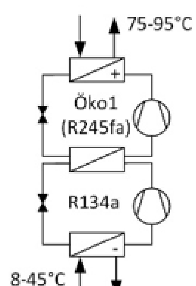
(Dürr thermea GmbH, 2016; IEA, 2014a; Thermea, 2012)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
20/80 (60)	3.9-4.3

Ochsner IWHS 400 ER3 screw compressor, 380 kW

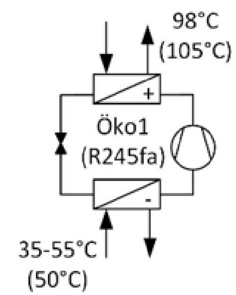
(Ochsner, 2015)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
45/90 (45)	4.0

Ochsner IWDS 330 ER3 screw compressor, 312 kW

(Zauner, 2016)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/105 (55)	2.68

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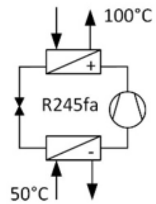
Commercial HTHPs – cycles, COPs and pictures

Combitherm

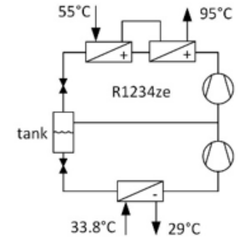
(Blesl et al., 2014; Wolf et al., 2014)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/100 (50)	3.1-3.4

Friotherm Unitop 22/22
3'300 kW, 2-stage turbo

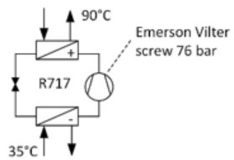
(Friotherm AG, 2005; Wojtan, 2016)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
34/95 (61)	3.51

Star Refrigeration
Neatpump NP601
380 kW to 2.6 MW, Vilter
VSSH screw 76 bar

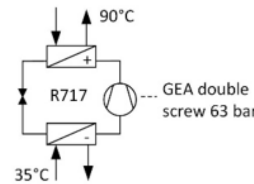
(EMERSON, 2012)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/90 (40)	3-4
35/80 (45)	5
39/90 (51)	4

GEA Grasso FX P
Heat Pump
Double screw 63 bar

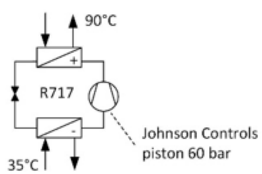
(Dietrich and Fredrich, 2012)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
35/80 (45)	5.0

Johnson Controls SABROE
HeatPAC™-HPX
piston compressor 60 bar

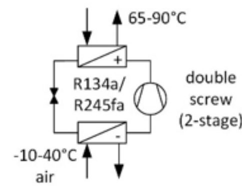
(Johnson Controls, 2017)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
39/90 (51)	4.0

Kobelco HEM-HR90
double screw (2-stage)

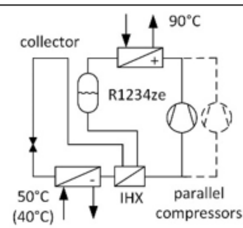
(Kuromaki, 2012; Oue and Okada, 2013)



T_{LT}/T_{HT} (ΔT_{Lift})	COP
17/90 (73)	4.5
35/90 (55)	5.8

Viessmann
Vitocal 350-HT Pro

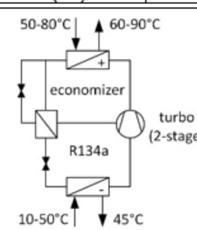
(Viessmann, 2016)



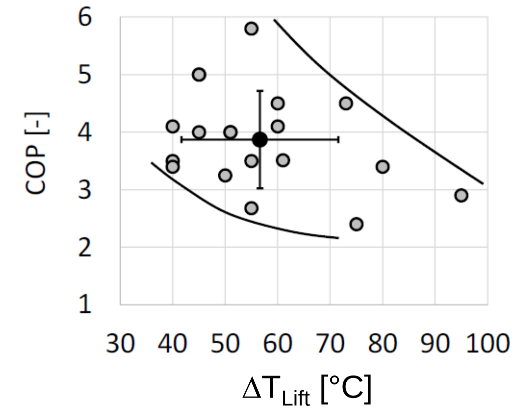
T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/90 (40)	3.4

Mitsubishi ETW-L

(IEA, 2014a; Watanabe, 2013).



T_{LT}/T_{HT} (ΔT_{Lift})	COP
50/90 (40)	4.1



COP vs. temperature lift
for various commercial HTWPs

Average values:
COP = 3.9 ± 0.8
ΔT_{Lift} = 57 ± 15 K

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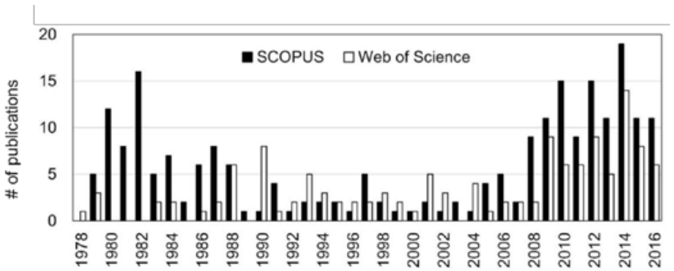
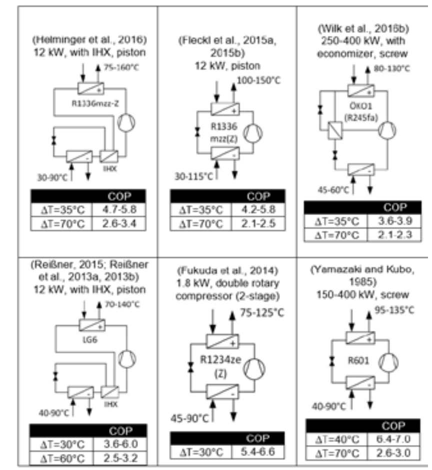
Research status on HTHPs –
Publications, projects, cycles, operating ranges

Publications



Which laboratory setups already exist?

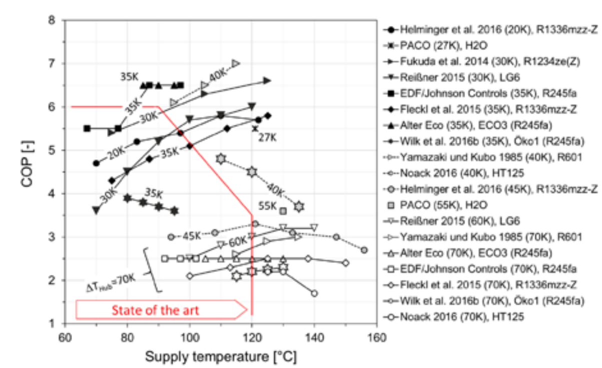
Cycles



Research projects

Organisation, Project partners	Cycle	Compressor type	Refrigerant	Source and supply temperatures [°C] (20 40 60 80 100 120 140 160)	Heating capacity [kW]	Reference
Austrian Institute of Technology (AIT), Wien, Chemours, Bitzer	IHX	piston	R1336mzz-Z		12	(Helminger et al., 2016)
Austrian Institute of Technology (AIT), Wien, Chemours, Bitzer	1-stage	piston	R1336mzz-Z		12	(Fleckl et al., 2015a, 2015b)
PACO, University Lyon, EDF Electricité de France	flash tank	double screw	H_2O (Wasser)		300	(Chamoun et al., 2014, 2013, 2012a, 2012b)
Institut für Luft- und Kältetechnik (ILK), Dresden	1-stage	n.a.	HT 125		12	(Noack, 2016)
Friedrich-Alexander Universität Erlangen-Nürnberg, Siemens	IHX	piston	LG6		10	(Reißner, 2015; Reißner et al., 2013a, 2013b)
Alter ECO, EDF Electricité de France	IHX and subcooler	double scroll	ECO3 (R245fa)		50-200	(Bobelin et al., 2012; IEA, 2014a)
Tokyo Electric Power Company, Japan	1-stage	screw	R601		150-400	(Yamazaki and Kubo, 1985)
Austrian Institute of Technology (AIT), Wien, Edtmayer, Ochsner	economizer	screw	ÖKO1 (R245fa)		250-400	(Wilk et al., 2016b)
Kyushu University, Fukuoka, Japan	1-stage	double rotary (2-stage)	R1234ze(Z)		1.8	(Fukuda et al., 2014)
Johnson Controls, EDF Electricité de France	economizer and IHX	double screw centrifugal turbo	R245fa		300-500 900-1'200	(IEA, 2014a)

COP vs. supply temperature

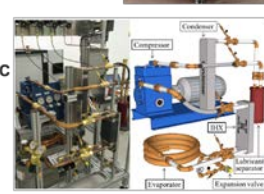


Experimental setups

160°C

Helminger (2016), Fleckl (2015)
AIT, Vienna
IHX, piston
(Bitzer 2CES),
R1336mzz(Z)

140°C



Reißner (2015, 2013), Erlangen
IHX, piston (GEA Bock E3), LG6

140°C

Noack (2016), ILK, Dresden
1-stage, HT 125

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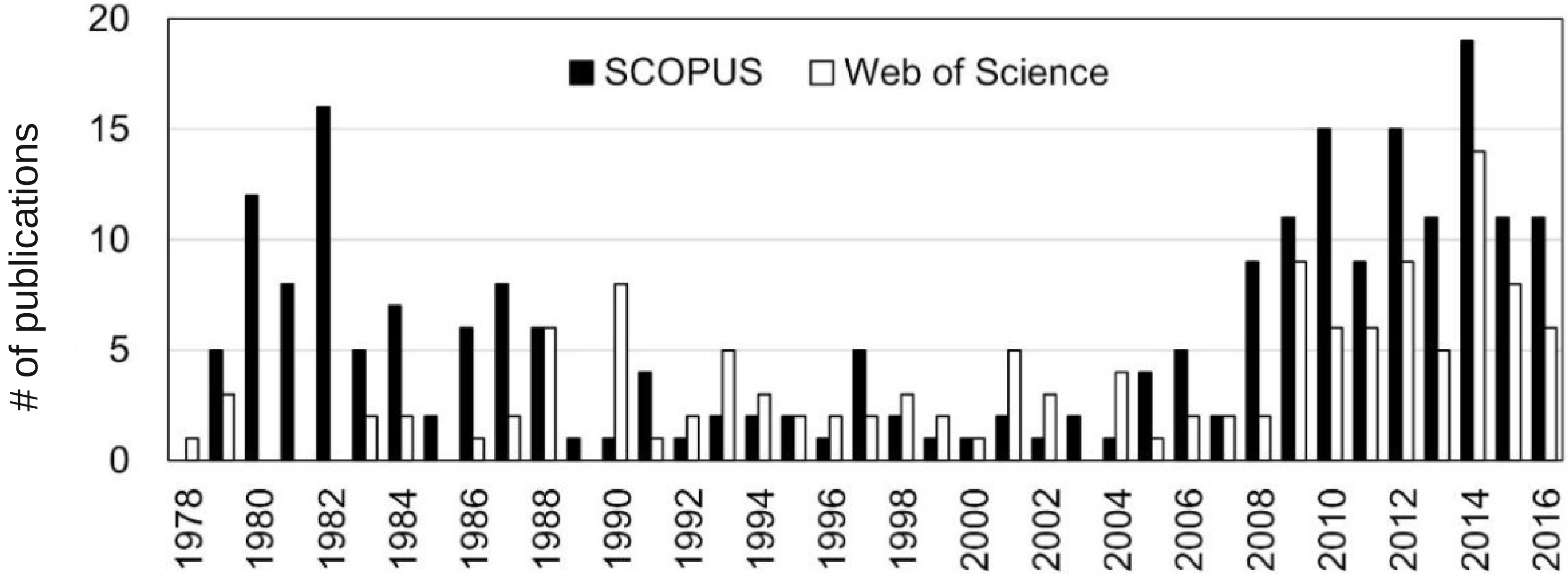
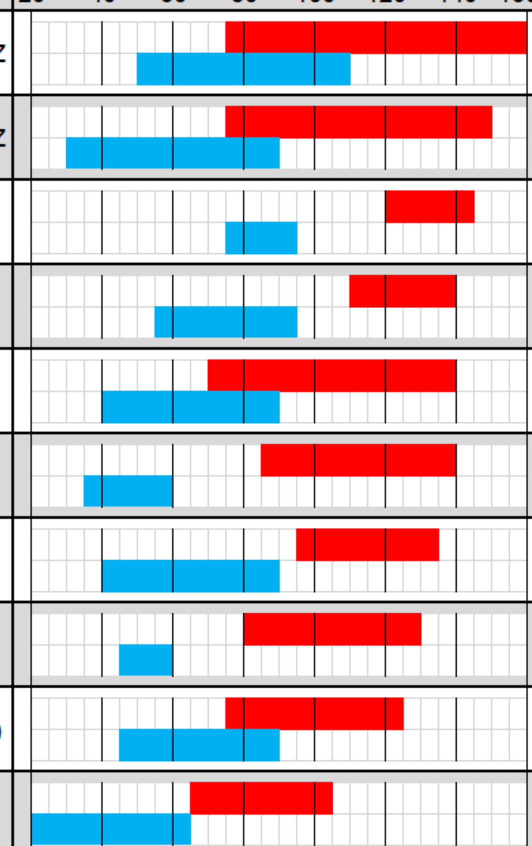
Research activity on HTHPs – Number of publications



Number of publications with search key word «high temperature heat pump» in databases SCOPUS (www.scopus.com) and Web of Science (www.webofknowledge.com)

Experimental research projects on HTHPs

Organisation, Project partners	Cycle	Compressor type	Refrigerant	Source and supply temperatures [°C]	Heating capacity [kW]	Reference
				20 40 60 80 100 120 140 160		
Austrian Institute of Technology (AIT), Wien, Chemours, Bitzer	IHX	piston	R1336mzz-Z		12	(Helminger et al., 2016)
Austrian Institute of Technology (AIT), Wien, Chemours, Bitzer	1-stage	piston	R1336mzz-Z		12	(Fleckl et al., 2015a, 2015b)
PACO, University Lyon, EDF Electricité de France	flash tank	double screw	H_2O (Wasser)		300	(Chamoun et al., 2014, 2013, 2012a, 2012b)
Institut für Luft- und Kältetechnik (ILK), Dresden	1-stage	n.a.	HT 125		12	(Noack, 2016)
Friedrich-Alexander Universität Erlangen-Nürnberg, Siemens	IHX	piston	LG6		10	(Reißner, 2015; Reißner et al., 2013a, 2013b)
Alter ECO, EDF Electricité de France	IHX and subcooler	double scroll	ECO3 (R245fa)		50-200	(Bobelin et al., 2012; IEA, 2014a)
Tokyo Electric Power Company, Japan	1-stage	screw	R601		150-400	(Yamazaki and Kubo, 1985)
Austrian Institute of Technology (AIT), Wien, Edtmayer, Ochsner	economizer	screw	ÖKO1 (R245fa)		250-400	(Wilk et al., 2016b)
Kyushu University, Fukuoka, Japan	1-stage	double rotary (2-stage)	R1234ze(Z)		1.8	(Fukuda et al., 2014)
Johnson Controls, EDF Electricité de France	economizer and IHX	double screw centrifugal turbo	R245fa		300-500 900-1'200	(IEA, 2014a)



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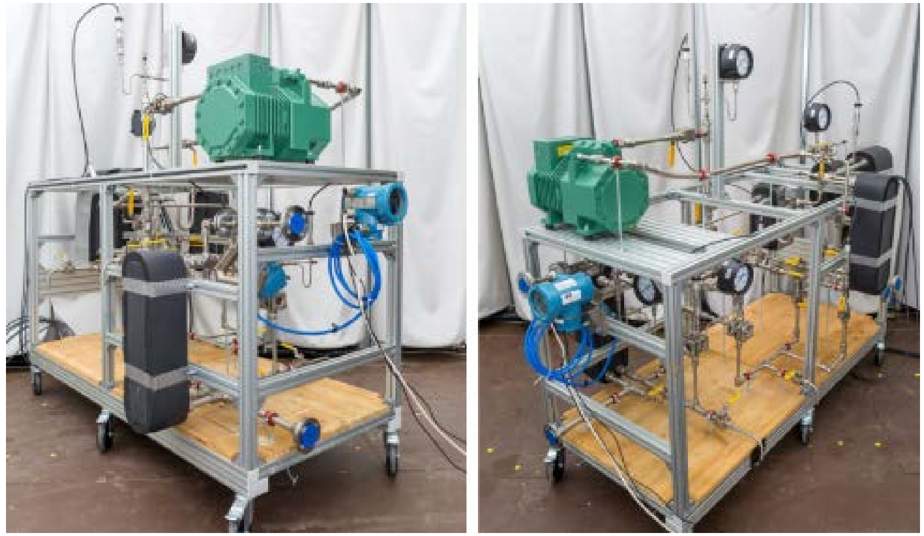
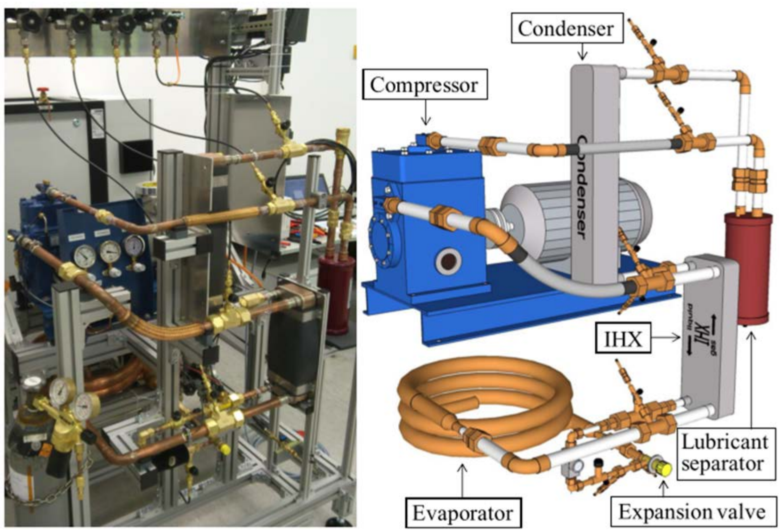
Experimental setups

160°C



Helminger (2016),
Fleckl (2015)
AIT, Vienna
1-stage cycle with IHX, piston (Bitzer 2CES), R1336mzz(Z)

140°C



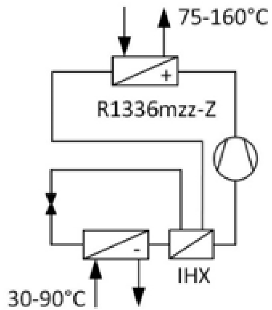
Reißner (2015, 2013), Erlangen
1-stage with IHX,
piston (GEA Bock E3), LG6

140°C

Noack (2016), ILK, Dresden
1-stage cycle, HT 125

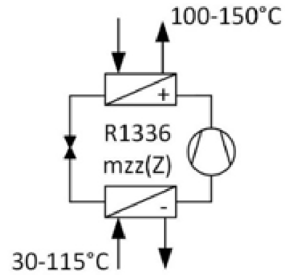
Cycles and achieved COPs of experimental research projects

(Helminger et al., 2016)
12 kW, with IHX, piston



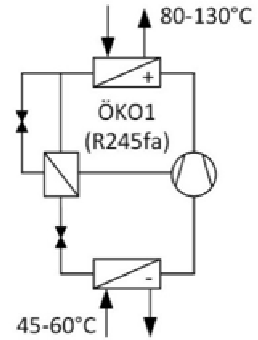
	COP
ΔT=35°C	4.7-5.8
ΔT=70°C	2.6-3.4

(Fleckl et al., 2015a, 2015b)
12 kW, piston



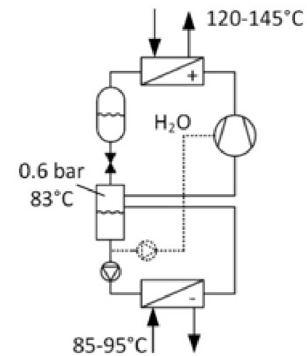
	COP
ΔT=35°C	4.2-5.8
ΔT=70°C	2.1-2.5

(Wilk et al., 2016b)
250-400 kW, with economizer, screw



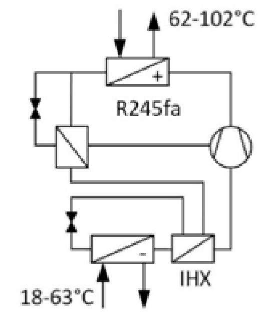
	COP
ΔT=35°C	3.6-3.9
ΔT=70°C	2.1-2.3

PACO project (Chamoun et al., 2014, 2013, 2012a, 2012b)
300 kW, with flash tank, double screw



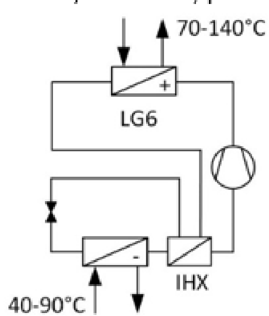
	COP
ΔT=27°C (94/121)	5.5
ΔT=55°C (75/130)	3.6

EDF/Johnson Controls (IEA, 2014a)
with economizer and IHX, 300-500 kW, double screw, 900-1'200 kW, turbo



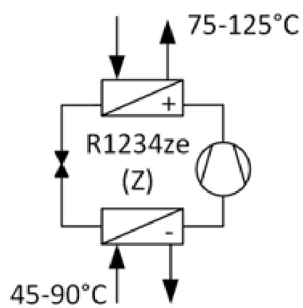
	COP
ΔT=35°C	5-7
ΔT=70°C	2-3

(Reißner, 2015; Reißner et al., 2013a, 2013b)
12 kW, with IHX, piston



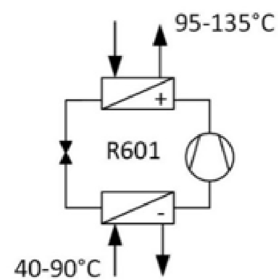
	COP
ΔT=30°C	3.6-6.0
ΔT=60°C	2.5-3.2

(Fukuda et al., 2014)
1.8 kW, double rotary compressor (2-stage)



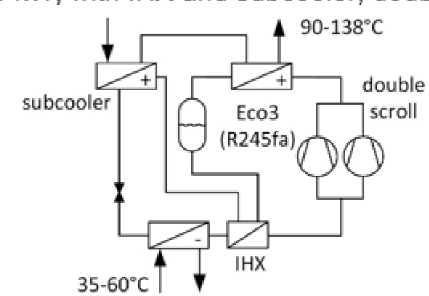
	COP
ΔT=30°C	5.4-6.6

(Yamazaki and Kubo, 1985)
150-400 kW, screw



	COP
ΔT=40°C	6.4-7.0
ΔT=70°C	2.6-3.0

Alter ECO project (Bobelin et al., 2012; IEA, 2014a)
50-200 kW, with IHX and subcooler, double scroll



	COP
ΔT=35°C	6-7
ΔT=70°C	2-3

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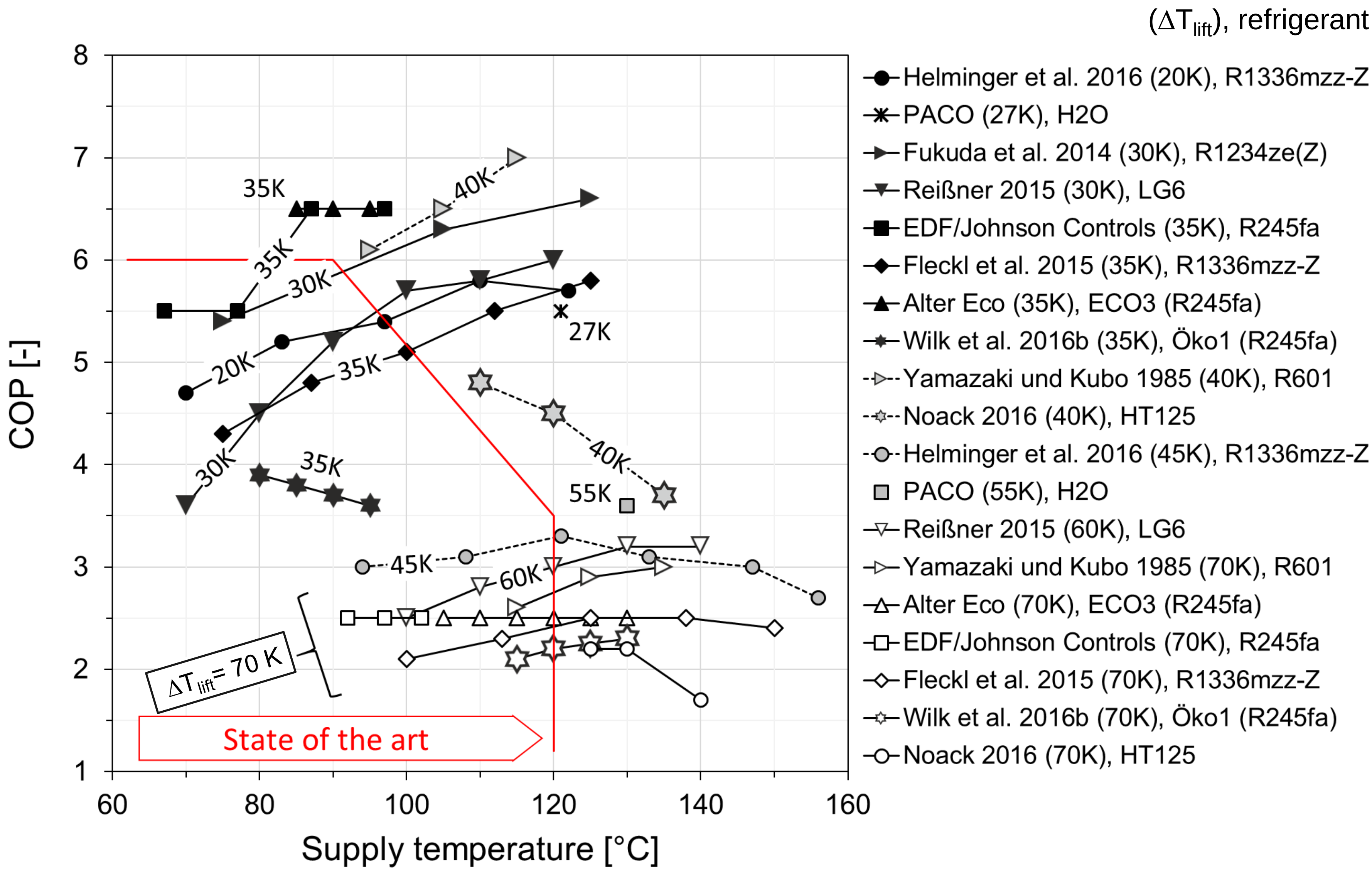
Achieved COPs of experimental research projects vs. supply temperature at constant temperature lifts (ΔT_{lift})



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Refrigerants for HTHPs

Which refrigerants are suitable for HTHPs?

Selection criteria

Criteria	Required properties
Thermal suitability	High critical temperature, low critical pressure
Environmental	ODP = 0, low GWP, 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 and copper

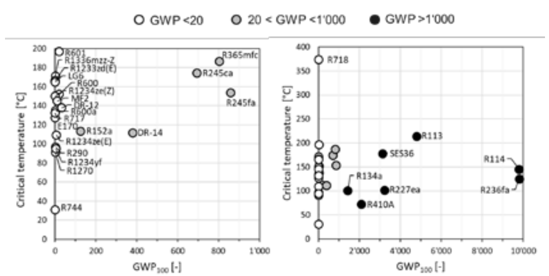
Price

Refrigerant	CAS Nr.	Container [kg]	Price per kg [Euro]	Factor to R134a
R134a	811-97-2	12	8.55	1.0
		28	8.55	1.0
		63	8.25	1.0
R410A	75-10-5 (50%) 354-33-6 50%)	10	8.85	1.0
		22	8.85	1.0
		53	8.60	1.0
R744	124-38-9	30	9.00	1.1
R1234ze(E)	1645-83-6	11	49.50	5.8
			69.90	8.2
		59	48.25	5.6
R1233zd		14	62.70	7.3
R245fa	460-73-1	14	63.65	7.4
			87.90	10.3
R1234yf	754-12-1	5	163.35	19.1
			229.60	26.9

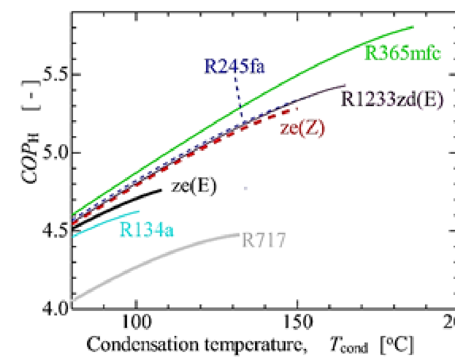
Refrigerant properties

Refrigerant	Description	Chemical formula	T_{crit} [°C]	p_{crit} [bar]	ODP [-]	GWP_{100} [-]	SG	Bp. [°C]	M [g/mol]
Ethane line									
R113	1,1,2-Trichloro-1,2,2-trifluoroethane	CCl_2FCClF_2	214.0	33.9	0.8	4'800	A1	47.6	187.4
R114	1,2-Dichloro-1,1,2,2-tetrafluoroethane	$CClF_2CClF_2$	145.7	32.6	1	9'800	A1	3.8	170.9
R134a	1,1,1,2-Tetrafluoroethane	CH_2FCF_3	101.1	40.6	0	1'430	A1	-26.1	102.0
R152a	1,1-Difluoroethane	CH_3CHF_2	113.3	45.2	0	124	A2	-24.0	66.1
Propane line									
R245ca	1,1,2,2,3-Pentafluoropropane	$CHF_2CF_2CH_2F$	174.4	39.3	0	693	n.v.	25.1	134.0
R245fa	1,1,2,2,3-Pentafluoropropane	$CHF_2CH_2CF_3$	154.0	36.5	0	858	B1	14.9	134.0
R236fa	1,1,1,3,3,3-Hexafluoropropane	$CF_3CH_2CF_3$	124.9	32.0	0	9'810	A1	-1.4	152.0
R227ea	1,1,1,2,3,3,3-Heptafluoropropane	CF_3CHFCF_3	101.8	29.3	0	3'220	A1	-15.6	170.0
R290	Propane	$CH_3CH_2CH_3$	96.7	42.5	0	3	A3	-42.1	44.1
R1270	Propene	$CH_3CH{=}CH_2$	91.1	45.6	0	2	A3	-47.6	42.1
Butane line									
R365mfc	1,1,1,3,3-Pentafluorobutane	$CF_3CH_2CF_2CH_3$	186.9	32.7	0	804	A2	40.2	148.1
SES36	Pentafluorobutane	R365mfc/PFPE65/35	177.6	28.5	0	3'126	A2	35.6	184.5
Hydrocarbons									
R601	Pentane	$CH_3CH_2CH_2CH_2CH_3$	196.6	33.7	0	20	A3	36.1	72.2
R600	Butane	$CH_3CH_2CH_2CH_3$	152.0	38.0	0	20	A3	-0.5	58.1
R600a	Isobutane	$CH(CH_3)_2CH_3$	134.7	36.3	0	3	A3	-11.8	58.1
Refrigerant mixtures									
R410A	R32/R125 (50/50)	CH_2F_2/CHF_2CF_3	72.6	49.0	0	2'088	A1	-51.5	72.6
Hydro Fluoro Olefines (HFOs)									
R1336mzz-Z	**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**
R1233zd(E)	**Tetrafluorpropene**	**$CF_3CH{=}CHCl$(trans)**	**166.5**	**36.2**	**0.0003**	**1**	**A1**	**18.0**	**130.5**
R1234ze(Z)	**cis-1,3,3,3-Tetrafluoro-1-propene**	**$CF_3CH{=}CHF$(cis)**	**150.1**	**35.3**	**0**	**1**	**A2**	**9.8**	**114.0**
R1234ze(E)	trans-1,3,3,3-Tetrafluoro-1-propene	$CF_3CH{=}CHF$(trans)	109.4	36.4	0	7	A2L	-19.0	114.0
R1234yf	2,3,3,3-Tetrafluoro-1-propene	$CF_3CF{=}CH_2$	94.7	33.8	0	4	A2L	-29.5	114.0
DR-14	n.a.	n.a.	111.6	39.6	0	380	A1	-20.5	n.v.
DR-12	n.a.	n.a.	137.7	30.0	0	32	1	7.5	n.v.
LG6	**n.a.**	**n.a.**	**165.0**	**n.a.**	**0**	**1**	**n.a.**	**n.a.**	**n.a.**
MF2	n.a.	n.a.	145.0	n.a.	0	10	n.a.	n.a.	n.a.
Others									
E170	Dimethyl ether	CH_3OCH_3	127.2	53.4	0	1	A3	-24.8	46.1
R718	Water	H_2O	373.9	220.6	0	0	A1	100.0	18.0
R717	Ammonia	NH_3	132.3	113.3	0	0	B2L	-33.3	17.0
R744	Carbon dioxide	CO_2	31.0	73.8	0	1	A1	-78.5	44.0

Critical temperature vs. GWP



Efficiency



Safety

	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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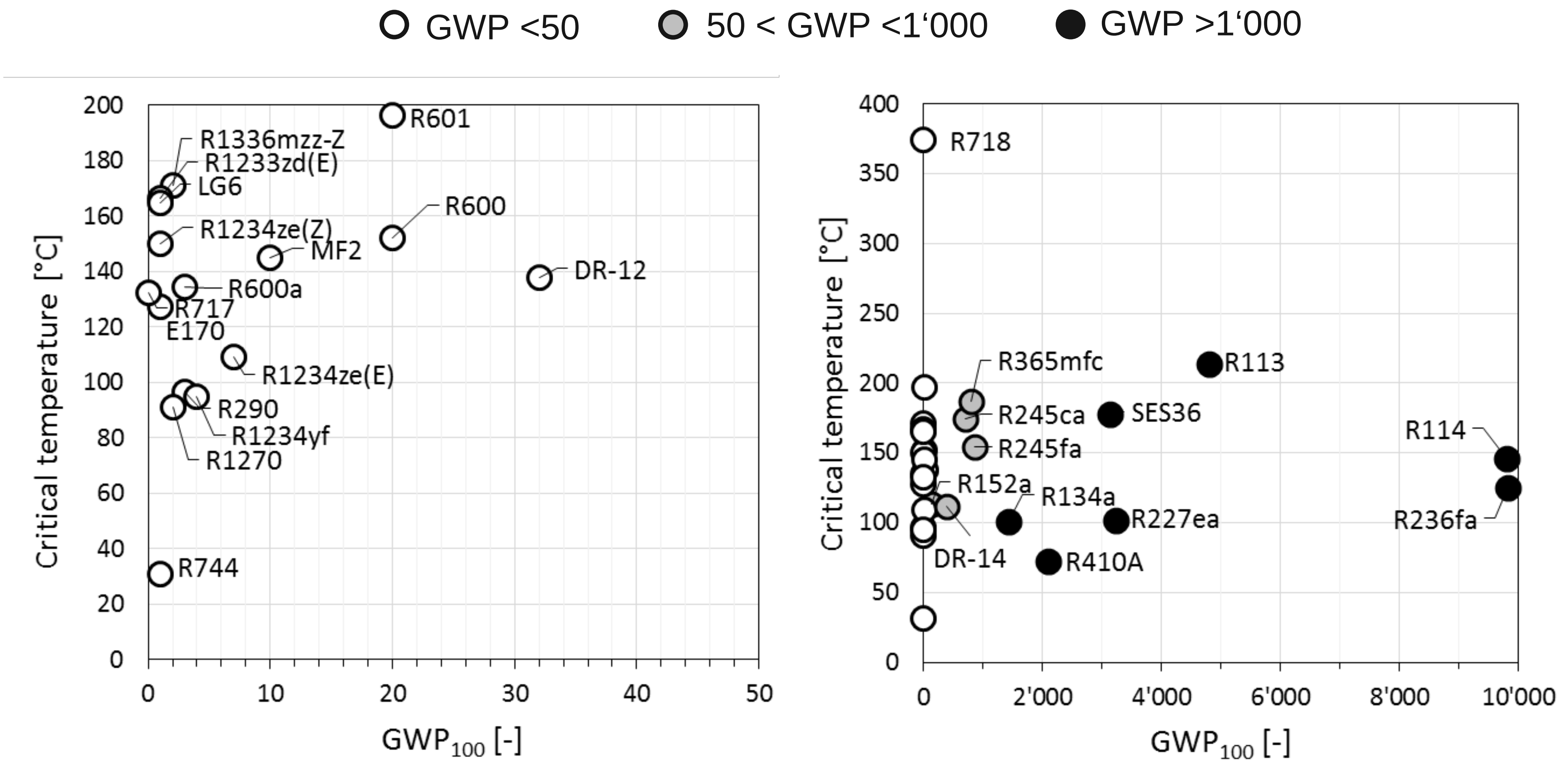
Refrigerants – selection criteria

Criteria	Required properties
Thermal suitability	High critical temperature, low critical pressure
Environmental	ODP = 0, low GWP, 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 and copper

Critical temperature vs. GWP



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Safety Group Classification

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			

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

Refrigerants – properties

Refrigerant	Description	Chemical formula	T_{crit} [°C]	p_{crit} [bar]	ODP [-]	GWP_{100} [-]	SG	Bp. [°C]	*M* [g/mol]
Ethane line									
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R1233zd(E)	**Tetrafluorpropene**	**$CF_3CH{=}CHCl$(trans)**	**166.5**	**36.2**	**0.0003**	**1**	**A1**	**18.0**	**130.5**
R1234ze(Z)	**cis-1,3,3,3-Tetrafluoro-1-propene**	**$CF_3CH{=}CHF$(cis)**	**150.1**	**35.3**	**0**	**1**	**A2**	**9.8**	**114.0**
R1234ze(E)	trans-1,3,3,3-Tetrafluoro-1-propene	$CF_3CH{=}CHF$(trans)	109.4	36.4	0	7	A2L	-19.0	114.0
R1234yf	2,3,3,3-Tetrafluoro-1-propene	$CF_3CF{=}CH_2$	94.7	33.8	0	4	A2L	-29.5	114.0
DR-14	n.a.	n.a.	111.6	39.6	0	380	A1	-20.5	n.v.
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LG6	**n.a.**	**n.a.**	**165.0**	**n.a.**	**0**	**1**	**n.a.**	**n.a.**	**n.a.**
MF2	n.a.	n.a.	145.0	n.a.	0	10	n.a.	n.a.	n.a.
Others									
E170	Dimethyl ether	CH_3OCH_3	127.2	53.4	0	1	A3	-24.8	46.1
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R744	Carbon dioxide	CO_2	31.0	73.8	0	1	A1	-78.5	44.0

T_{crit} = critical temperature

p_{crit} = critical pressure

ODP = Ozone Depletion Potenial (R11=1.0)

GWP = Global Warming Potential (CO2=1.0, 100 years EU F-Gas regulation 517/2014)

SG = Safety group (DIN EN 378-1, 2008, ASHRAE 34)

Bp. = Boiling point at 1.013 bar

M = Molecular weight

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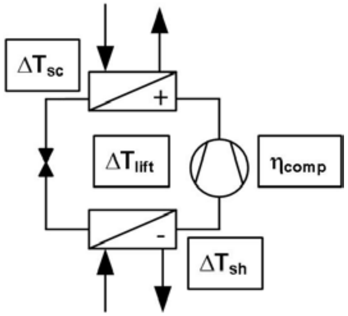
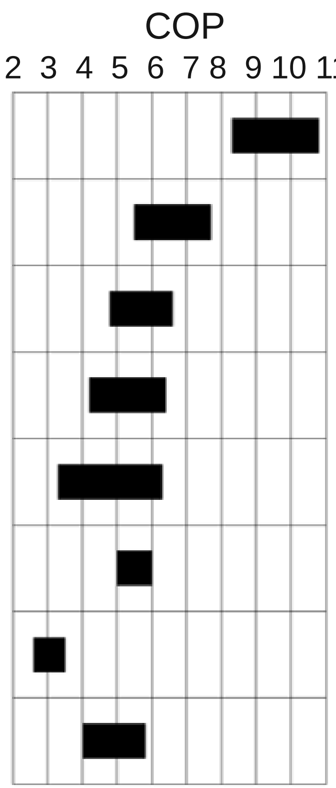
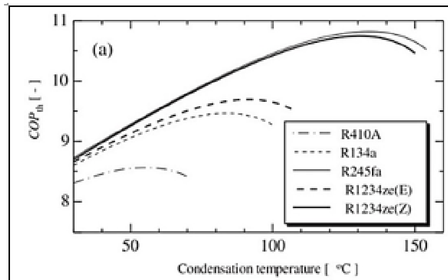
Theoretical studies – Efficiency range for 1-stage cycles with different refrigerants



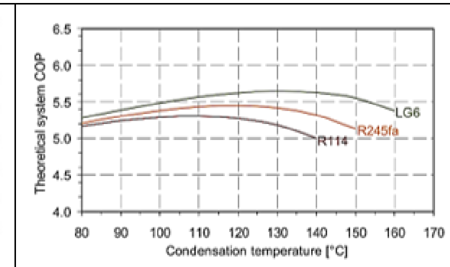
ΔT_{lift}: temperature lift
ΔT_{sh}: superheating
ΔT_{sc}: subcooling
η_{comp}: isentropic compressor efficiency

Reference	ΔT_{sh}	ΔT_{sc}	η_{comp}	ΔT_{lift}
	[K]	[K]	[-]	[K]
Fukuda et al. (2014)	3	20	1	35
Kontomaris (2014)	5	5	0.8	35
IEA (2014), Kontomaris (2015, 2013)	11	5	0.8	40
Duclos et al. (2014)	10	5	0.75	45
Reißner (2015)	5	5	0.8	50
Reißner et al. (2013)	5	5	0.8	50
IEA (2014), Kontomaris (2015, 2013)	20	5	0.8	70
Kondou and Koyama (2015)	3	60	1	80

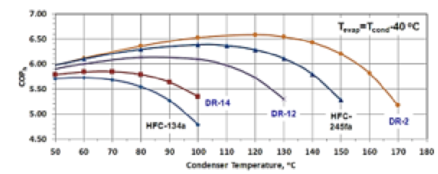




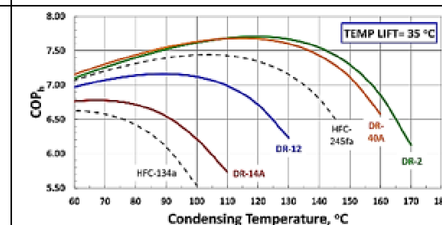
(Fukuda et al., 2014)



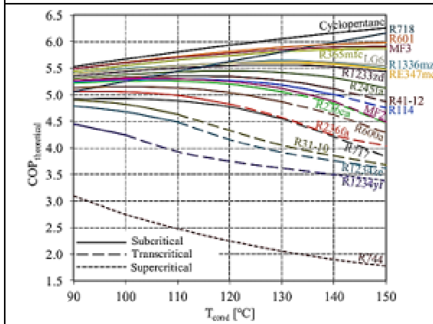
(Reißner et al., 2013b)



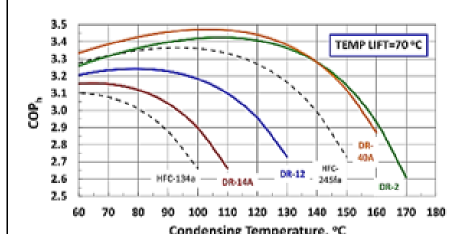
(IEA, 2014a; Kontomaris, 2015, 2013)



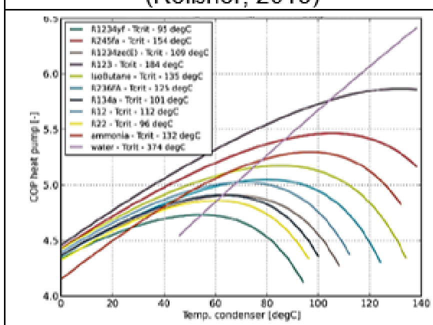
(Kontomaris, 2014c)



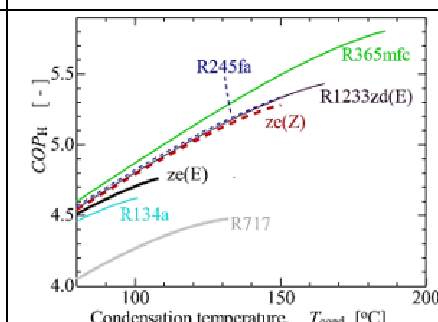
(Reißner, 2015)



(IEA, 2014a; Kontomaris, 2015, 2013)



(Duclos et al., 2014)



(Kondou and Koyama, 2015)

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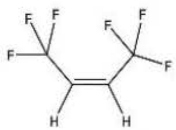
Possible concept for a HTHP laboratory prototype

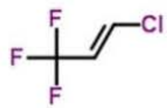
HFO refrigerants

R1336mzz(Z)



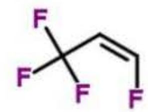
171.3°C
29.0 bar
A1

R1233zd(E)



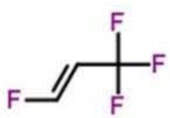
166.5°C
36.2 bar
A1

R1234ze(Z)



150.1°C
35.3 bar
A2L

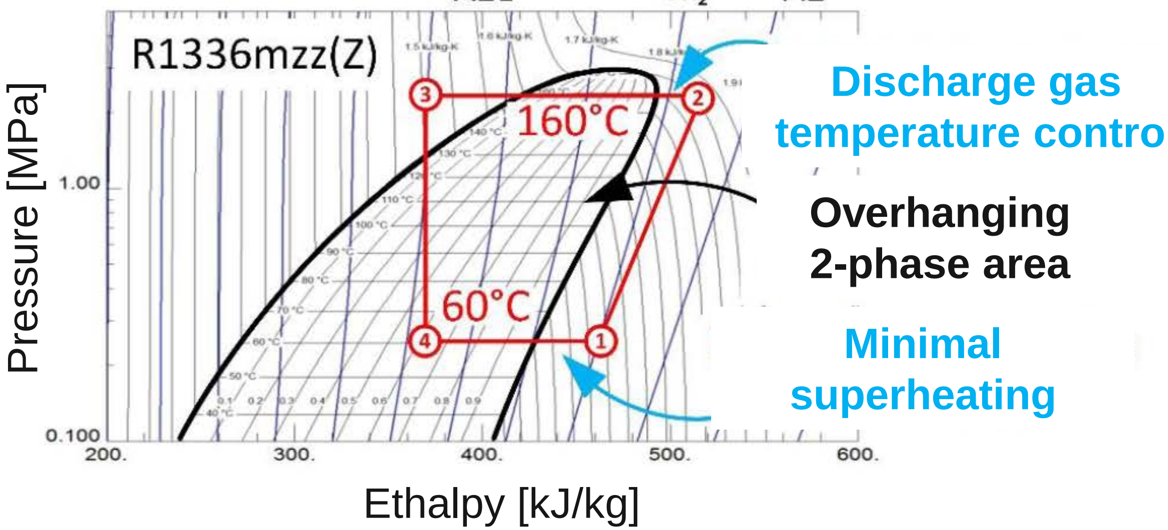
R1234ze(E)



109.4°C
36.4 bar
A2L

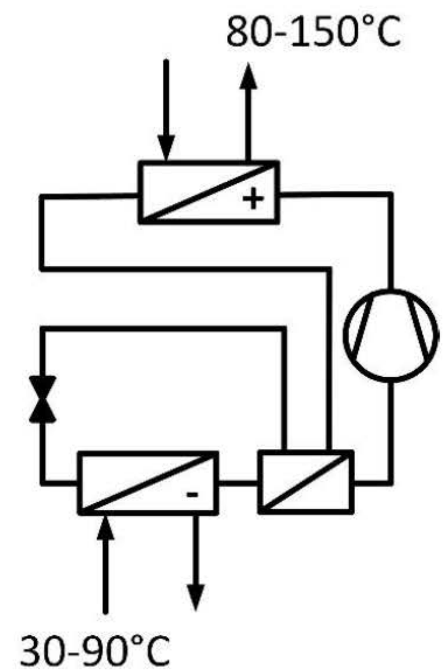
R1234yf

94.7°C
33.8 bar
A2



Cycle

1-stage with IHX



<u>Decition criteria:</u>

1) Thermodynamic suitability (T_{crit} > 150°C, allows subcritical, good efficiency at high temperatures)
2) Environmental compatibility (GWP <10, ODP = 0, future-proof according to F-Gas regulation)
3) Safety (no or only low flammability)
4) Natural refrigerants R600 and R600a excluded due to flammability (A3), other refrigerants due to lack of information and availability

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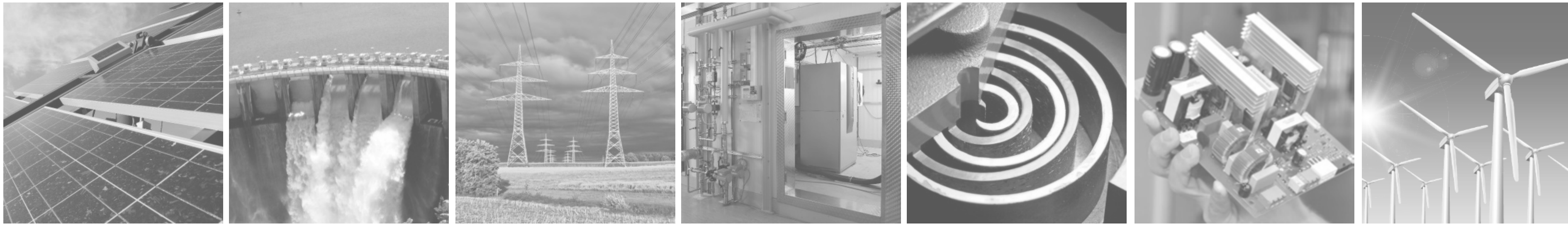
Conclusions – Market overview

- **More than 20 HTHP models** identified with supply temperatures > 90°C from 13 manufacturers (e.g. Vicking HeatBooster with 150°C, Ochsner IWWDS with 130°C, Kobelco SGH120, Mayekawa Eco Sirocco, and Hybrid Energy Heat Pump with 120°C)
- **Heat source:** water, brine, waste heat (17 to 65°C)
- **COP:** 2.4 to 5.8 at a temperature lift of 40 to 95 K
- **Heating capacity:** from about 20 kW to 20 MW
- **Refrigerants:** R245fa, R717 (NH_3), R744 (CO_2), R134a, R1234ze(E)
- **Compressors:** 1- and 2-shaft screws, 2-stage turbo, pistons (parallel)
- **Cycles:** usually 1-stage, optimization by IHX, parallel compressors, economizer, intermediate injection, 2-stage cascade (R134a/R245fa) or with a flash economizer

Conclusions – Research status

- **Highest supply temperature of 160°C** at AIT (Vienna), 1-stage cycle with IHX and R1336mzz(Z)
- **At least 10 research projects** reached > 100°C
- **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)
- **Cycles all 1-stage:** partly with IHX and/or economizer with intermediate injection
- **Refrigerants:** R1336mzz(Z), R718 (H2O), R245fa, R1234ze (Z), R601, LG6 (Siemens), ÖKO1 (contains R245fa, Ochsner), ECO3 (R245fa, Alter ECO), HT125 (ILK, Dresden)
- **Compressors:** piston in lab systems
- **HFO refrigerants:** thermodynamic suitable, good efficiency, GWP <10, ODP = 0, safe, future-proof according to F-Gas regulation



Thank you for your attention!

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