American Council for an Energy-Efficient Economy

OST Eastern Switzerland University of Applied Sciences

Industrial Heat Pumps: Technology readiness, economic conditions, and sustainable refrigerants

Industrial Heat Pump Workshop at ACEEE Industrial Summer Study, 11 July 2023, Detroit, USA

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Content

- Motivation for industrial heat pumps
- Technology readiness and commercial HTHPs with supply > 100 °C
- Innovations occurring in the market – new developments and products
- Summary and conclusions

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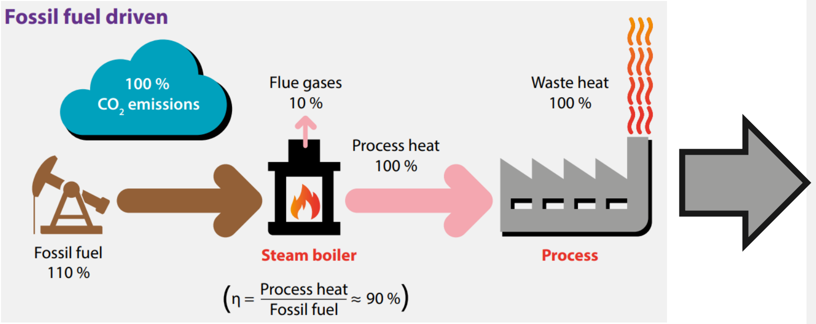
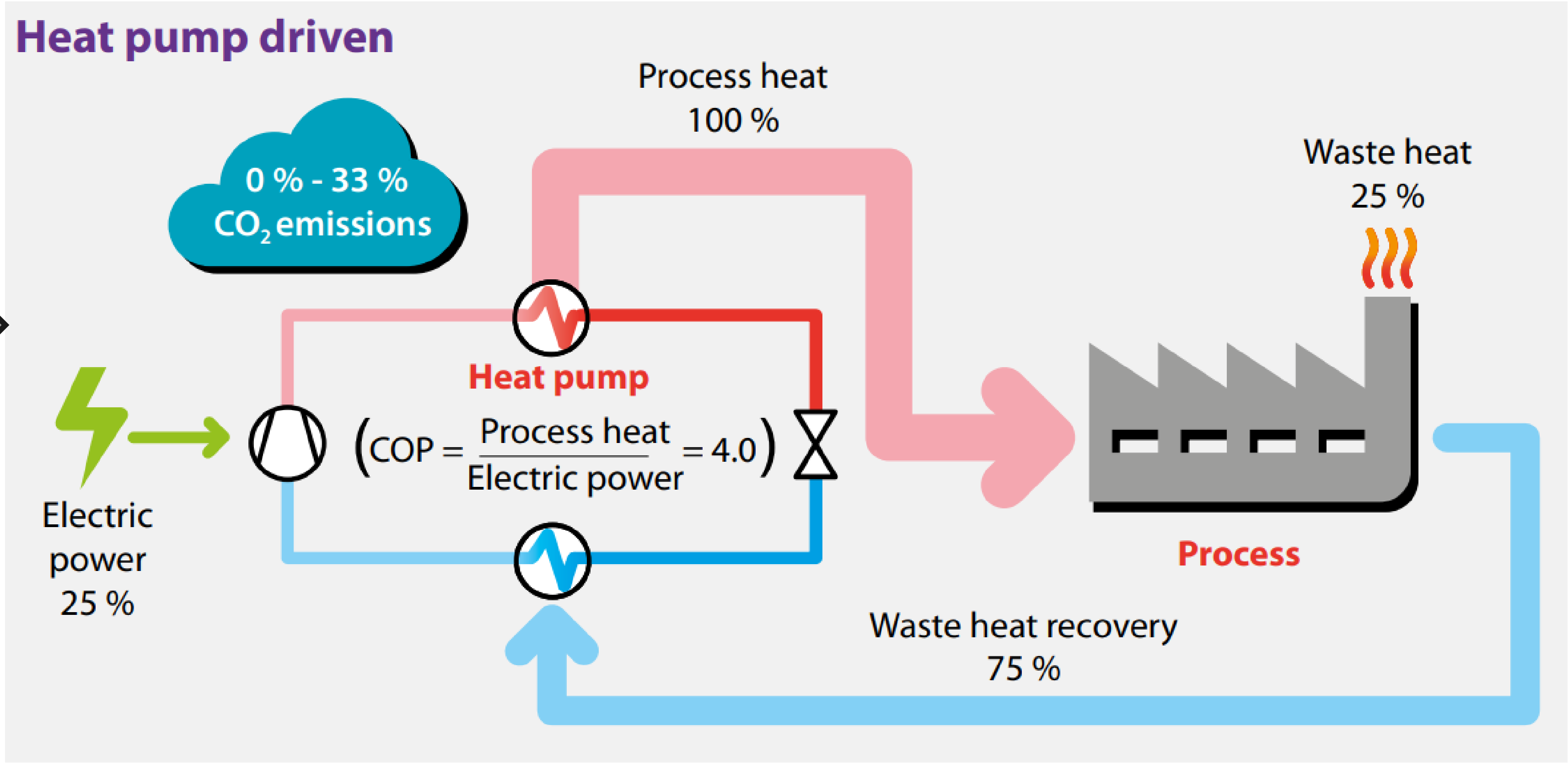
Motivation

What is the role of heat pumps in an electrified industry?





Source: De Boer, R., Marina, A., Zühlsdorf, B., Arpagaus, C., Bantle, M., Wilk, V., Elmegaard, B., Corberán, J., Benson, J.: Strengthening Industrial Heat Pump Innovation: Decarbonizing Industrial Heat, 14 July 2020, Download White Paper

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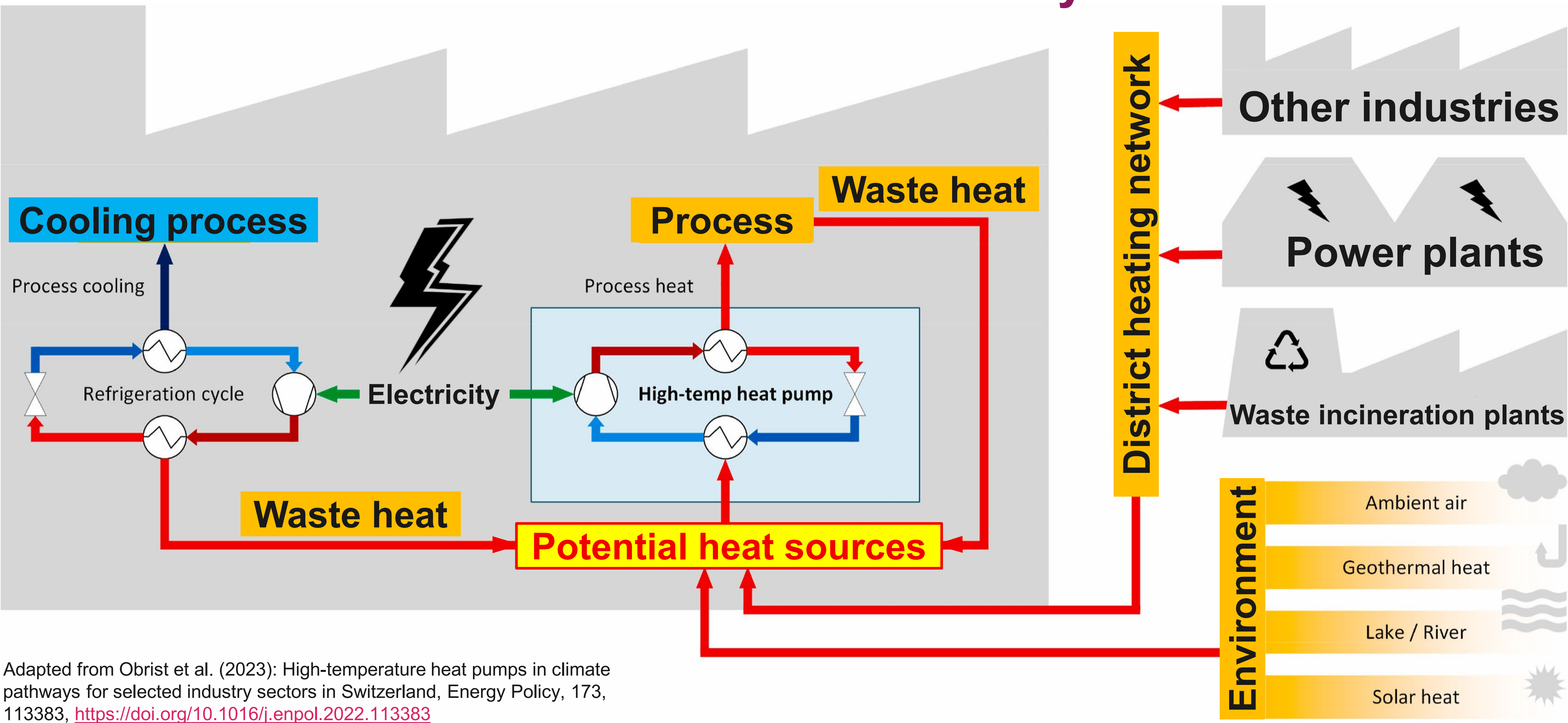
Motivation

Potential heat sources for HTHPs in industry



Adapted from Obrist et al. (2023): High-temperature heat pumps in climate pathways for selected industry sectors in Switzerland, Energy Policy, 173, 113383, https://doi.org/10.1016/j.enpol.2022.113383

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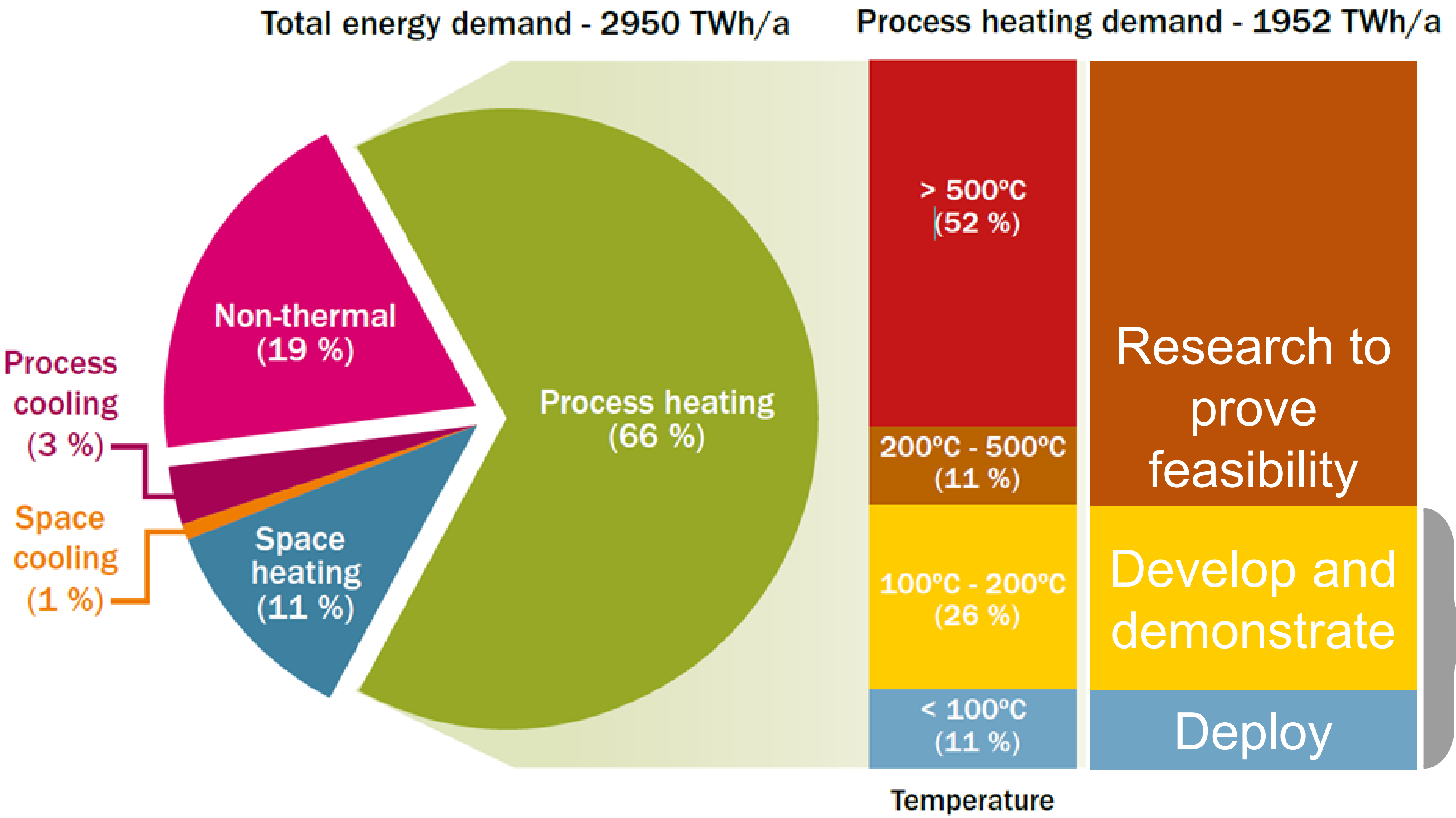
Motivation

Process Heat Demand in the European Industry



Heat pumps are identified as a key technology for the decarbonization of this share of the industrial heat supply (< 200 °C)

37% of the process heat required by the European industry is < 200 ºC (730 TWh/a)

Source: De Boer et al. (2020): White Paper, Strengthening Industrial Heat Pump Innovation, Decarbonizing Industrial Heat

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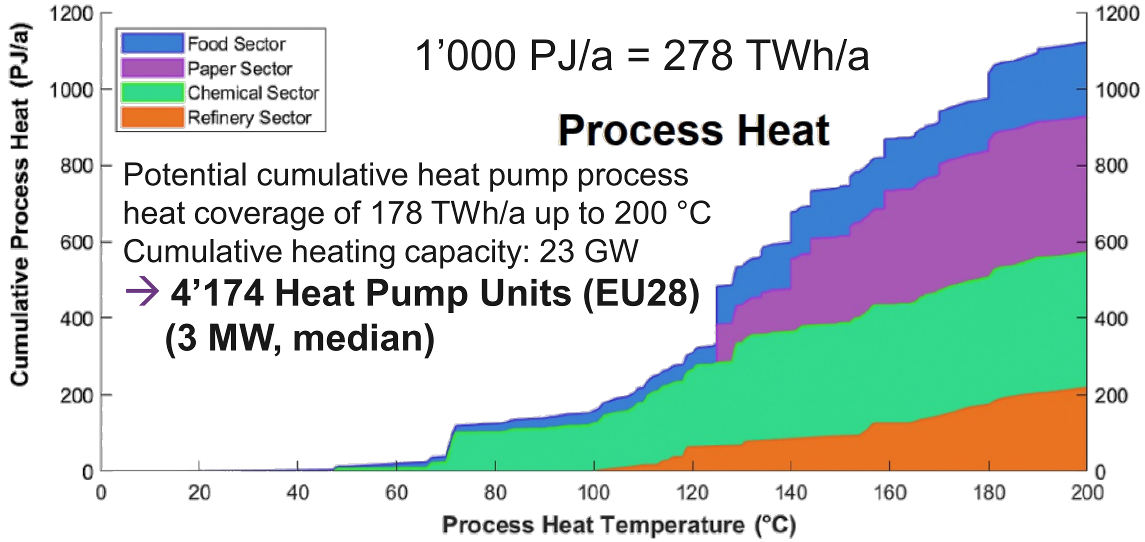
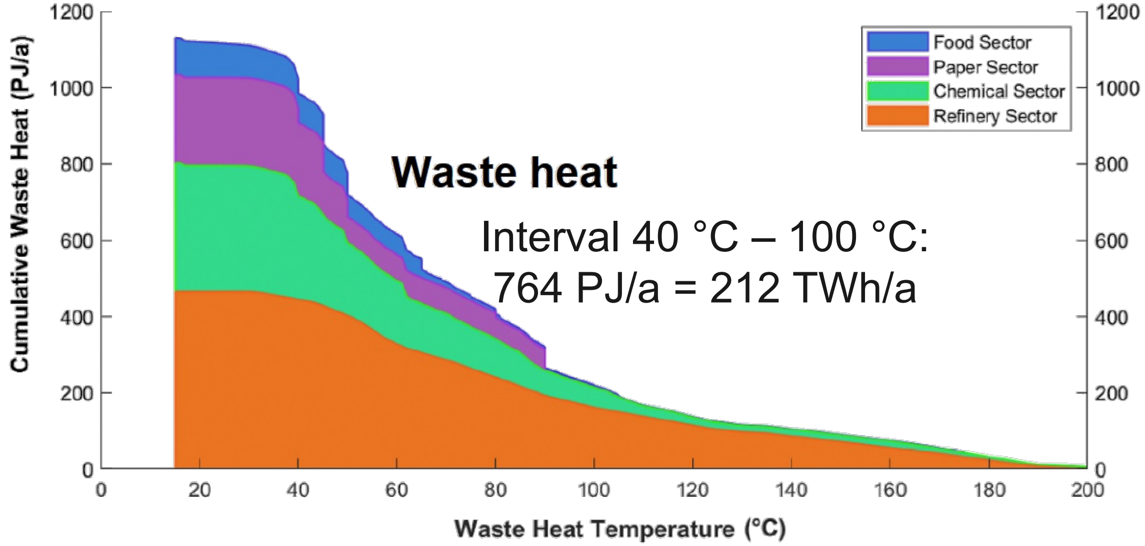
Motivation

The Role of High-Temperature Heat Pumps (HTHP)





The heat pump market potential to 200 °C is large:

- Highest potential in the **food, paper, and chemical sectors**
- Available **waste heat** between 40 °C and 100 ºC is estimated to be 212 TWh/a (764 PJ/a) (EU28)
- … but still, **the actual market of industrial heat pumps is emerging**

Source: Marina et al. (2021): An estimation of the European industrial heat pump market potential, Renewable and Sustainable Energy Reviews, 139, 110545, https://doi.org/10.1016/j.rser.2020.110545

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Temperature levels of industrial processes

Sector	Process	[°C]
Paper	Drying	90 -240
	Boiling	110 - 180
	Bleaching	40 - 150
	De-inking	50 - 70
Food & beverages	Drying	40 - 250
	Evaporation	40 - 170
	Pasteurization	60 - 150
	Sterilization	100 - 140
	Boiling	70 - 120
	Distillation	40 - 100
	Blanching	60 - 90
	Scalding	50 - 90
	Concentration	60 - 80
	Tempering	40 - 80
	Smoking	20 - 80
Chemicals	Destillation	100 - 300
	Compression	110 - 170
	Thermoforming	130 - 160
	Concentration	120 - 140
	Boiling	80 - 110
	Bioreactions	20 - 60
Automotive	Resin molding	70 - 130
Metal	Drying	60 - 200
	Pickling	20 - 100
	Degreasing	20 - 100
	Electroplating	30 - 90
	Phosphating	30 - 90
	Chromating	20 - 80
	Purging	40 - 70

Sector	Process	[°C]
Plastic	Injection modling	90 - 300
	Pellets drying	40 - 150
	Preheating	50 - 70
Mechanical engineering	Surface treatment	20 - 120
	Cleaning	40 -90
Textiles	Coloring	40 - 160
	Drying	60 - 130
	Washing	40 - 110
	Bleaching	40 - 100
Wood	Glueing	120 - 180
	Pressing	120 - 170
	Drying	40 - 150
	Steaming	70 - 100
	Cocking	80 - 90
	Staining	50 - 80
	Pickling	40 - 70
Several sectors	Hot water	20 - 110
	Preheating	20 - 100
	Washing/Cleaning	30 - 90
	Space heating	20 - 80

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

Source: Arpagaus et al. (2018): Review on High-Temperature Heat Pumps, https://doi.org/10.1016/j.energy.2018.03.166

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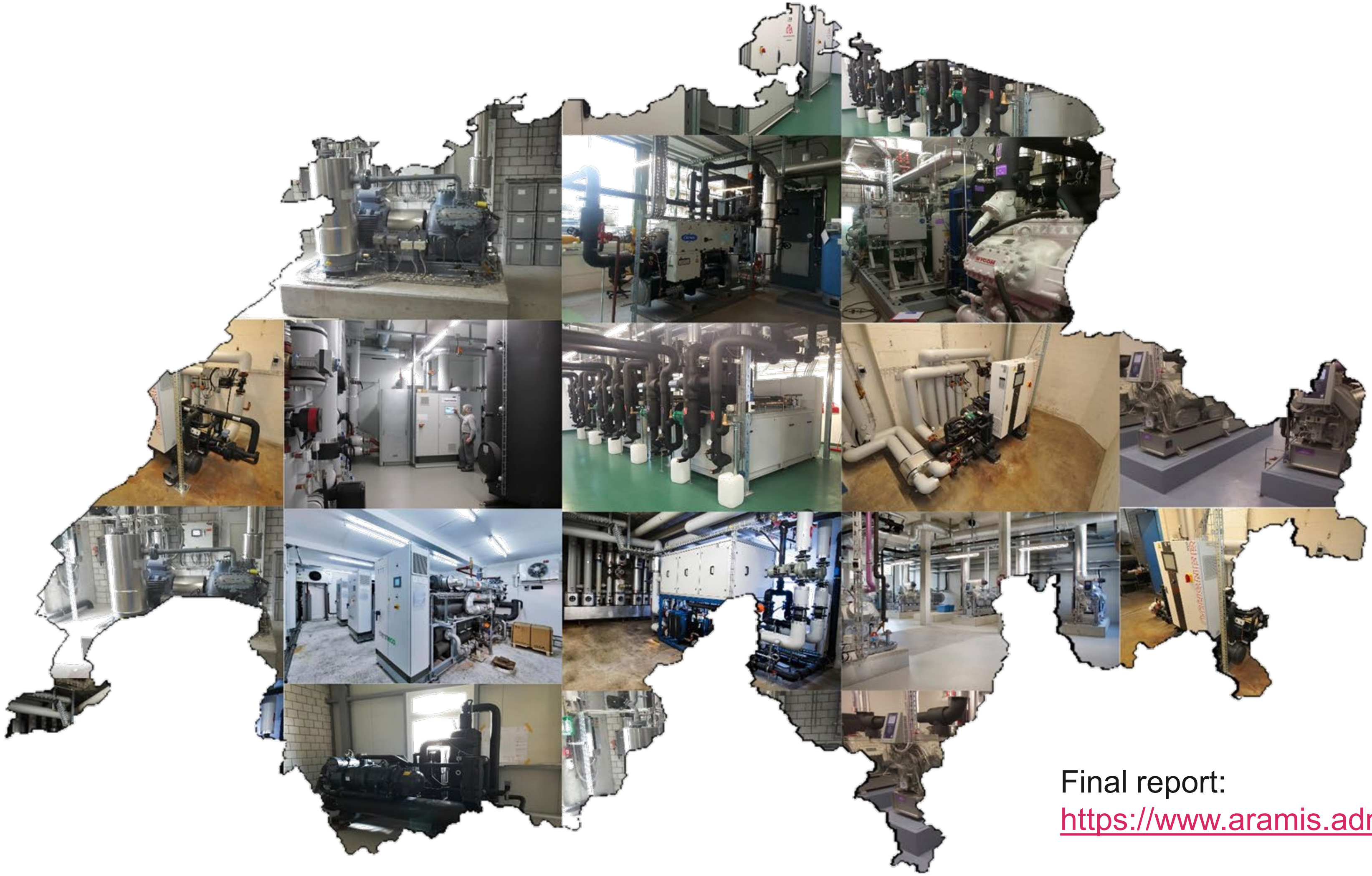
Case studies of Industrial Heat Pumps in Switzerland



- Presents case studies of successful applications of industrial heat pumps in Switzerland
- Promotes further market penetration of industrial heat pumps
- Highlights typical applications in large-scale
- Establishes a framework for comparison

Final report:
https://www.aramis.admin.ch/Dokument.aspx?DocumentID=66033

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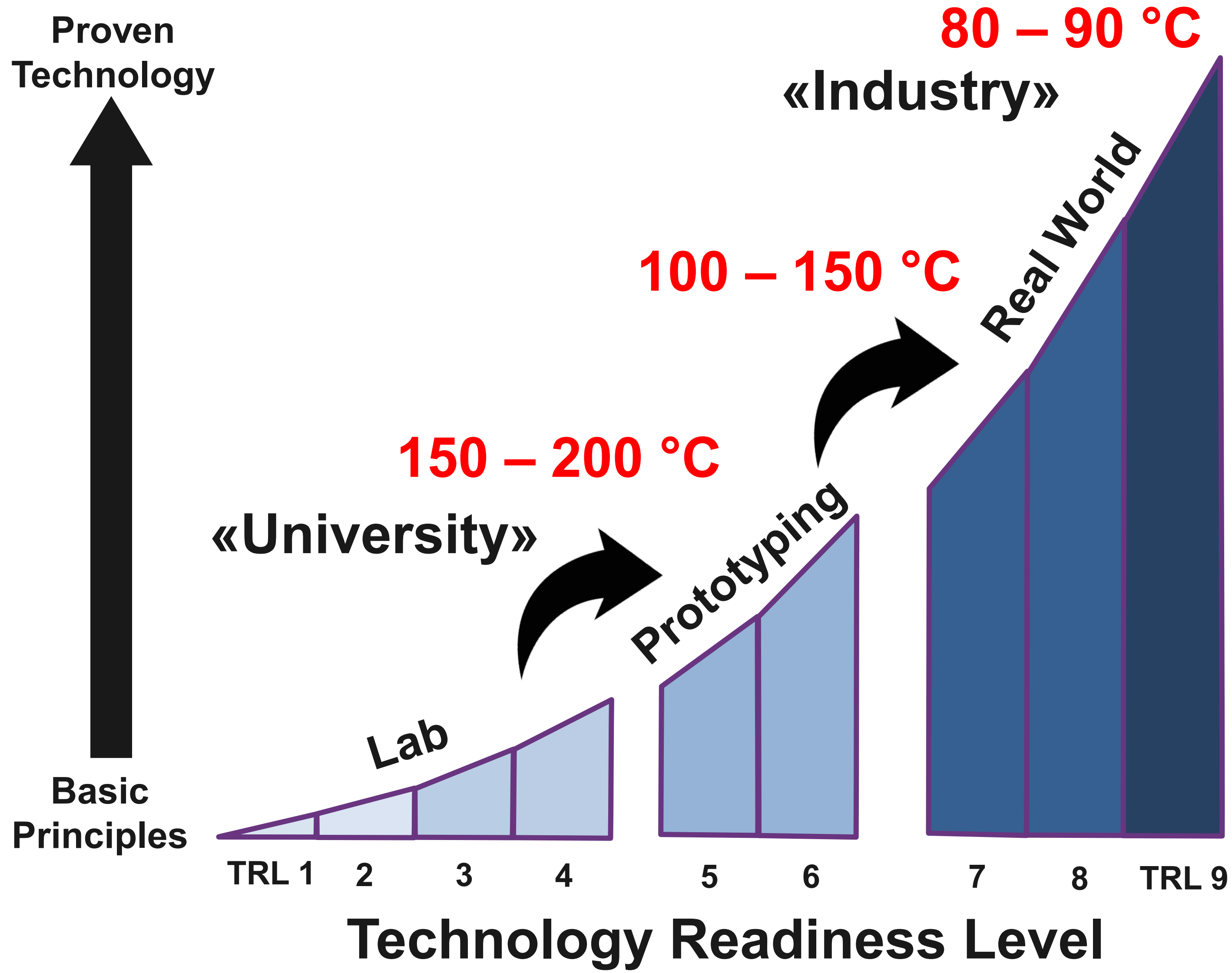
What is the Technology Readiness Level (TRL) of HTHP ?



Technology Readiness Levels (TRL)	
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant (industrial) environment
TRL 6	Technology demonstrated in relevant (industrial) environment
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment

Source: TRL scale definition in Horizon Europe projects, https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

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Comparison of different HTHP supplier technology

Facts about the HTHP technology

- Heat supply capacity
- Temperature range
- Working fluid (refrigerant)
- Compressor technology
- Specific investment costs
- TRL level
- Expected lifetime (years)
- Size (weight, footprint)

EPCON Evaporation Technology AS
ecop
MAN Energy Solutions
enerin Energy Engineering
QPINCH
PILLER Blowers & Compressors
Weel & Sandvig Energy and Process Innovation
Fuji Electric
SPILLING Technologies
TURBODEN clean energy ahead
KOBELCO
MAYEKAWA MYCOM
Rank®
EMERSON
SIEMENS energy
toCircle Industries
SABROE Johnson Controls
:skala fabrikk
SRM
SPH Sustainable Process Heat
FENAGY Future Energy Solutions
HEATEN
MITSUBISHI HEAVY INDUSTRIES THERMAL SYSTEMS
OLVONDO Technology
HybridEnergy

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HTHP Technologies

Indicated TRL levels

- **23 market available (TRL 8-9)**
- **7 prototype and demonstration systems (TRL 6-7)**
- **3 lab/small-scale prototypes (TRL 4-5)**

HTHP supplier (High-Temperature Heat Pump)	Product	Max. heating capacity (MW)	Max. supply temp. (°C)	TRL (Technology Readiness Level)								
				1	2	3	4	5	6	7	8	9
Spilling	Steam Compressor	15	**280**									9
Enerin	HoegTemp	10	**250**						6			
Qpinch	Heat Transformer	2	**230**									9
Piller	VapoFan	70	**212**								8	9
Olvondo	HighLift	5	**200**									9
Turboden	LHP	30	**200**							7	8	9
ToCircle	TC-C920	5	**188**						6	7		
Kobelco MSRC160	MSRC160	0.8	**175**									9
Kobelco SGH165	SGH165	0.62	**175**									9
Heaten	HeatBooster	6	**165**							7	8	9
SPH	Thermbooster	5	**165**						6	7	8	
SRM	Compressor for water vapor	2	**165**					5				
Siemens Energy	Industrial Heat Pump	70	**160**									9
Enertime	HTHPs	10	**160**				4	5	6	7	8	
Weel & Sandvig	WS Turbo Steam	5	**160**				4	5	6	7	8	9
Rank	Rank® HP	2	**160**							7		
MAN	ETES CO_2 Heat Pump	50	**150**							7	8	
Epcon	MVR-HP	30	**150**									9
Ohmia Industry	SPHP	10	**150**							7	8	
ecop	Rotation Heat Pump K7	0.7	**150**						6	7		
Mayekawa FC Comp	FC-compressor	1	**145**					5				
GEA Refrigeration	CO_2 Heat Pump	1.2	**130**								8	
Mitsubishi Heavy Ind.	ETW-S	0.6	**130**									9
Hybrid Energy	HyPAC-S	5	**120**									9
Johnson Controls	Cascade Heat Pump System	5	**120**							7	8	
Fenagy	H1800-AW/WW	1.8	**120**					5	6			
Mayekawa HS Comp	HS-compressor	0.75	**120**							7		
Kobelco SGH120	SGH120	0.37	**120**									9
Mayekawa EcoSirocco	Eco Sirocco	0.1	**120**									9
Fuji Electric	Steam Generation Heat Pump	0.03	**120**									9
Emerson	Cascade Solution	0.03	**120**						6			
Skala Fabrikk	SkaleUP	0.3	**115**							7		
Mayekawa EcoCircuit	Eco Circuit 100	0.1	**100**								8	9

Other suppliers:
- Ago Calora (150 °C)
- Ochsner (130 °C)
- Oilon (120 °C)
- PureThermal (120 °C)
- ThermoDraft (120 °C)
- Combitherm (120 °C)
- …

Large-scale:
- Friotherm
- MAN Energy Solutions
- Turboden
- Mitsubishi MHPS
- Siemens Energy
- …

Data source: IEA HPT Annex 58
https://heatpumpingtechnologies.org/annex58/task1

Note:

All information has been provided by the suppliers without third-party validation.

The information was provided as an indicative basis and may be different in final installations depending on application-specific parameters.

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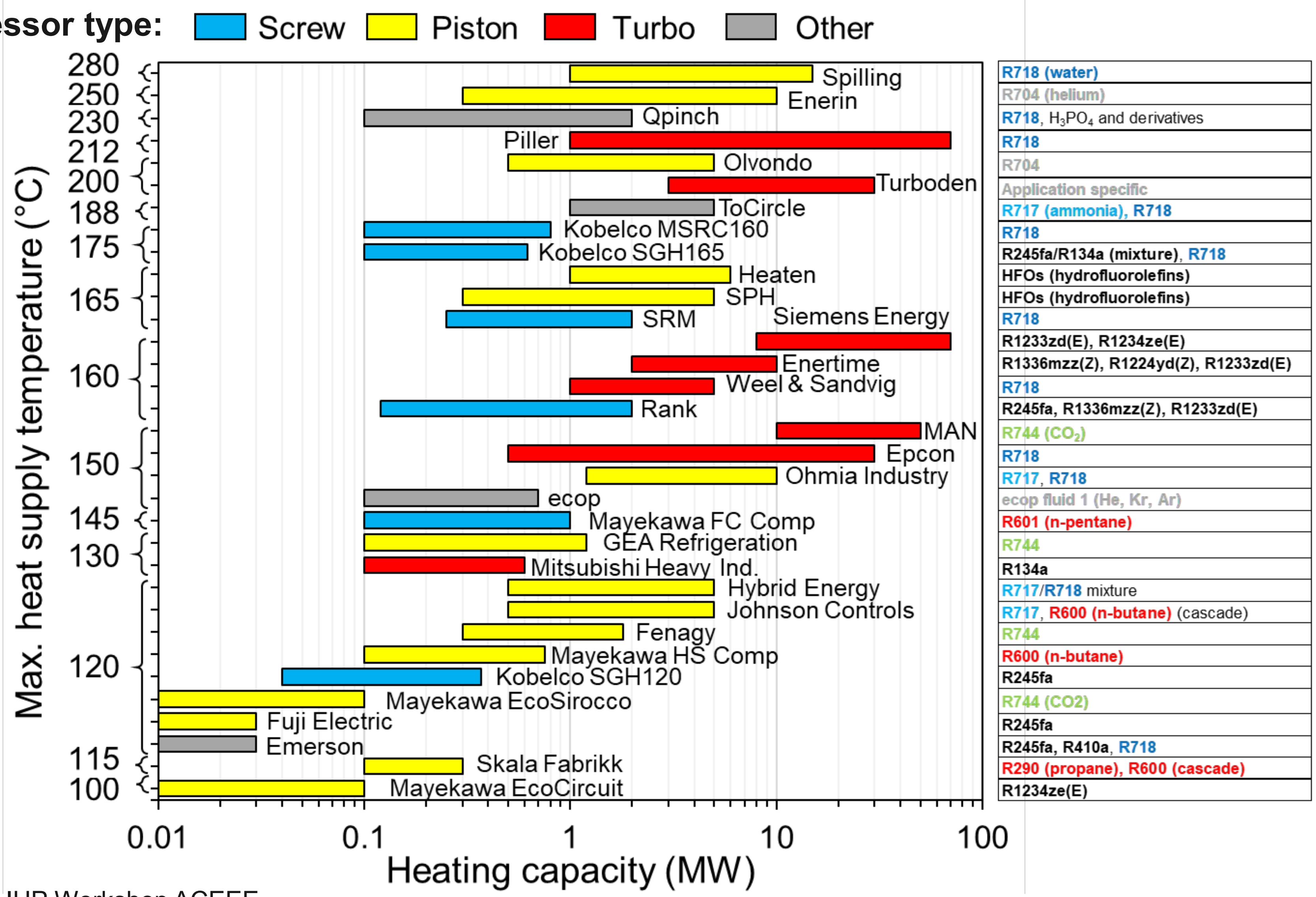
Commercial High-Temperature Heat Pumps for Supply Temperatures > 100 °C

Max. supply temperature vs. heating capacity of various HTHPs



Refrigerant

R718 (Water)
R704 (Helium)
R717 (Ammonia)
HFOs (Hydrofluorolefine)
R744 (CO_2)
R601 (n-Pentane)
R600 (n-Butane)
R290 (Propane)

Source: Arpagaus et al. (2023): Integration of High-Temperature Heat Pumps in Swiss Industrial Processes (HTHP-CH) (494), 14th IEA Heat Pump Conference, 15-18 May 2023, Chicago, Illinois, USA

Based on data from IEA HPT Annex 58 https://heatpumpingtechnologies.org/annex58/task1

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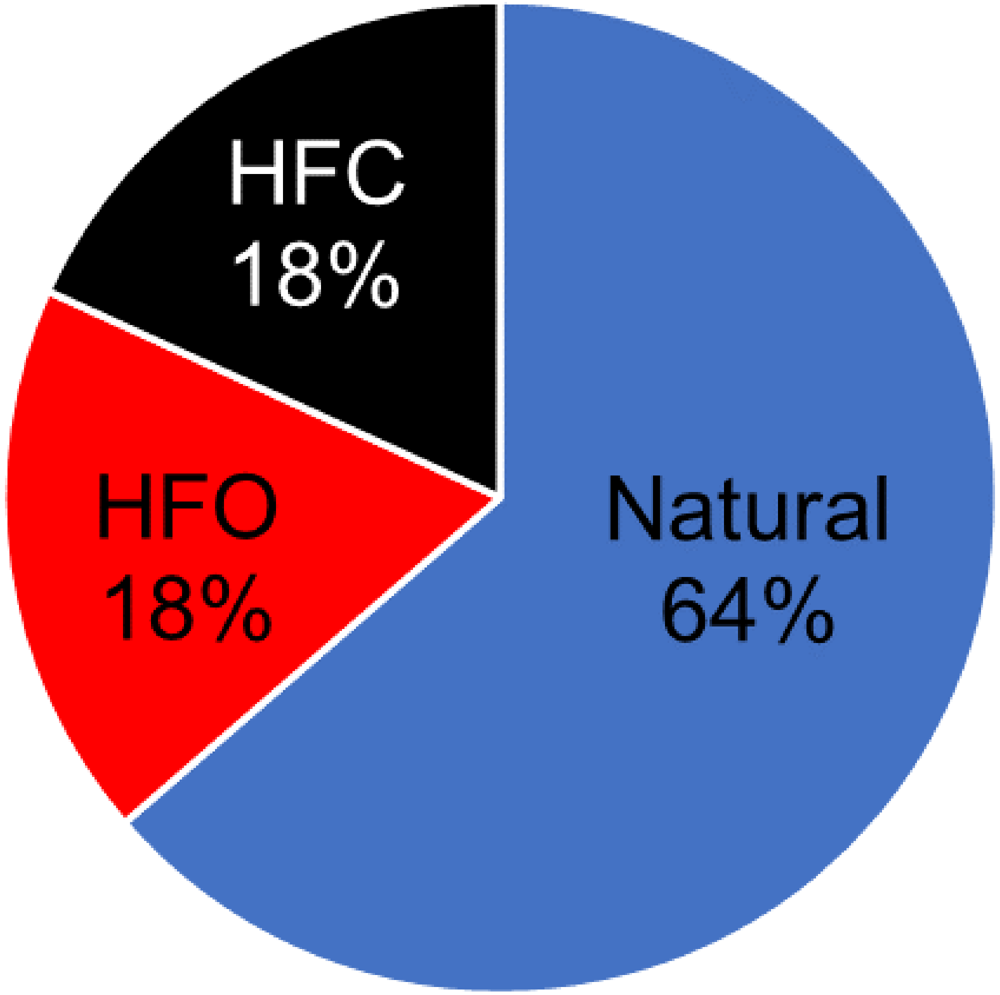
Refrigerants in HTHPs



R718 (Water)	12
R744 (CO2)	4
R717 (Ammonia)	4
R601 (n-Pentane)	1
R600 (n-Butane)	3
R290 (Propane)	1
R704 (Helium)	2
ecop (Nobel gas)	1
R1336mzz(Z)	2
R1233zd(E)	3
R1234ze(E)	1
HFOs	2
R245fa	5
R410a	1
R134a	2
Natural	28
HFO	8
HFC	8

Based on data from IEA HPT Annex 58
https://heatpumpingtechnologies.org/annex58/task1

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HTHP products for > 100 °C supply temperature

HTHP supplier (High-Temperature Heat Pump)	Country	Product	Compressor type	Working fluid (Refrigerant)	Max. heating capacity (MW)	Max. supply temp. (°C)	TRL (Technology Readiness Level)	Spec. invest. cost (EUR/kW_{th})
Spilling	DE	Steam Compressor	Piston (MVR)	R718 (water)	15	280	9	100 to 400
Enerin	NO	HoegTemp	Piston	R704 (helium)	10	250	6	600 to 800
Qpinch	BE	Heat Transformer	Chemical heat transformer	R718, H_3PO_4 and derivatives	2	230	9	1000 to 2000
Piller	DE	VapoFan	Turbo (MVR)	R718	70	212	8 to 9	850
Olvondo	NO	HighLift	Piston (double acting)	R704	5	200	9	1200
Turboden	IT	LHP	Turbo	Application specific	30	200	7 to 9	300 to 700
ToCircle	NO	TC-C920	Rotary vane	R717 (ammonia), R718	5	188	6 to 7	250 to 430
Kobelco MSRC160	JP	MSRC160	Twin -screw (MVR)	R718	0.8	175	9	n.a.
Kobelco SGH165	JP	SGH165	Twin-screw (MVR)	R245fa/R134a (mixture), R718	0.62	175	9	n.a.
Heaten	NO	HeatBooster	Reciprocating, custom design	HFOs (hydrofluoroolefins)	6	165	7 to 9	250 to 350
SPH	DE	Thermbooster	Piston	HFOs (hydrofluoroolefins)	5	165	6 to 8	150 to 1000
SRM	SE	Compressor for water vapor	Screw (MVR)	R718	2	165	5	n.a.
Siemens Energy	DE	Industrial Heat Pump	Turbo (geared or single-shaft)	R1233zd(E), R1234ze(E)	70	160	9 (to 90 °C)	250 to 800
Enertime	FR	HTHPs	1- or 2-stage centrifugal	R1336mzz(Z), R1224yd(Z), R1233zd(E)	10	160	4 to 8	300 to 400
Weel & Sandvig	DK	WS Turbo Steam	Turbo (MVR)	R718	5	160	4 to 9	150 to 250
Rank	ES	Rank® HP	Screw	R245fa, R1336mzz(Z), R1233zd(E)	2	160	7	200 to 400
MAN	DE	ETES CO_2 Heat Pump	Centrifugal turbo with expander	R744 (CO_2)	50	150	7 to 8	300 to 500
Epcon	NO	MVR-HP	Centrifugal fan / Blower	R718	30	150	9	200 to 400
Ohmia Industry	NO	SPHP	Piston, Centrifugal fan (MVR)	R717, R718	10	150	7 to 8	n.a.
ecop	AT	Rotation Heat Pump K7	Rotational heat pump	ecop fluid 1 (He, Kr, Ar)	0.7	150	6 to 7	700
Mayekawa FC Comp	BE	FC-compressor	Screw	R601 (n-pentane)	1	145	5	720
GEA Refrigeration	NL	CO_2 Heat Pump	Semi-hermetic piston	R744	1.2	130	8	200 to 300
Mitsubishi Heavy Ind.	JP	ETW-S	Two-stage centrifugal	R134a	0.6	130	9	n.a.
Hybrid Energy	NO	HyPAC-S	Piston/screw	R717/R718 mixture	5	120	9	200 to 600
Johnson Controls	DK	Cascade Heat Pump System	Reciprocating	R717, R600 (n-butane) (cascade)	5	120	7 to 8	n.a.
Fenagy	DK	H1800-AW/WW	Reciprocating	R744	1.8	120	5 to 6	250 to 425
Mayekawa HS Comp	BE	HS-compressor	Piston	R600 (n-butane)	0.75	120	7	450
Kobelco SGH120	JP	SGH120	2-stage twin-screw	R245fa	0.37	120	9	n.a.
Mayekawa EcoSirocco	JP	Eco Sirocco	Reciprocating	R744 (CO2)	0.1	120	9	n.a.
Fuji Electric	JP	Steam Generation Heat Pump	Reciprocating	R245fa	0.03	120	9	n.a.
Emerson	US	Cascade Solution	Scroll and EVI scroll	R245fa, R410a, R718	0.03	120	6	n.a.
Skala Fabrikk	NO	SkaleUP	Piston (semihermetic)	R290 (propane), R600 (cascade)	0.3	115	7	500 to 700
Mayekawa EcoCircuit	JP	Eco Circuit 100	Reciprocating	R1234ze(E)	0.1	100	8 to 9	n.a.

Data source:
IEA HPT Annex 58
https://heatpumpingtechnologies.org/annex58/task1

Note:

All information has been provided by the suppliers without third-party validation.

The information was provided as an indicative basis and may be different in final installations depending on application-specific parameters.

Other suppliers:
- Ago Calora (150 °C)
- Ochsner (130 °C)
- Oilon (120 °C)
- PureThermal (120 °C)
- ThermoDraft (120 °C)
- Combitherm (120 °C)
- …

Large-scale:
- Friotherm
- MAN Energy Solutions
- Turboden
- Mitsubishi MHPS
- Siemens Energy
- …

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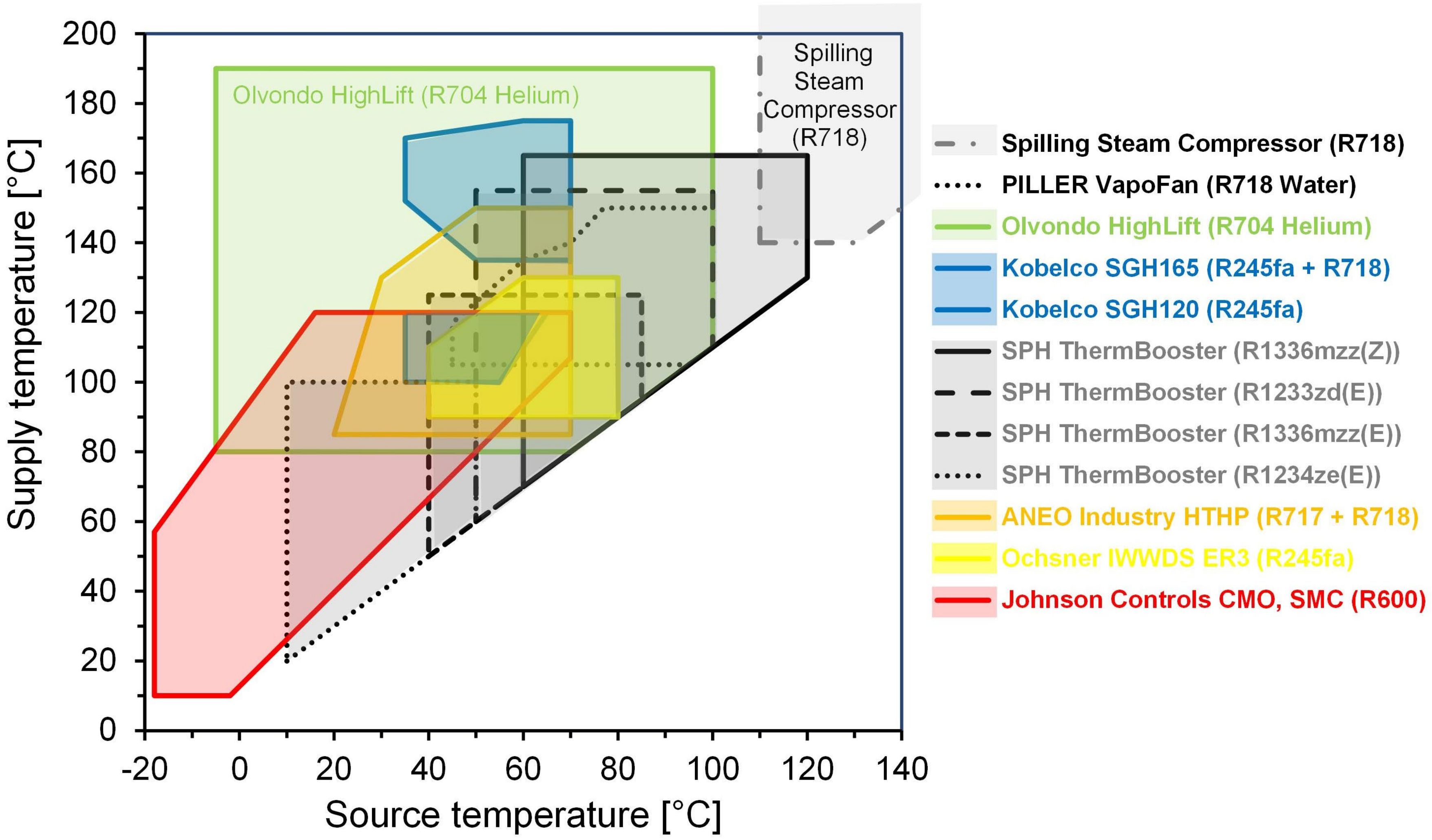
Operating maps of some industrial HTHPs



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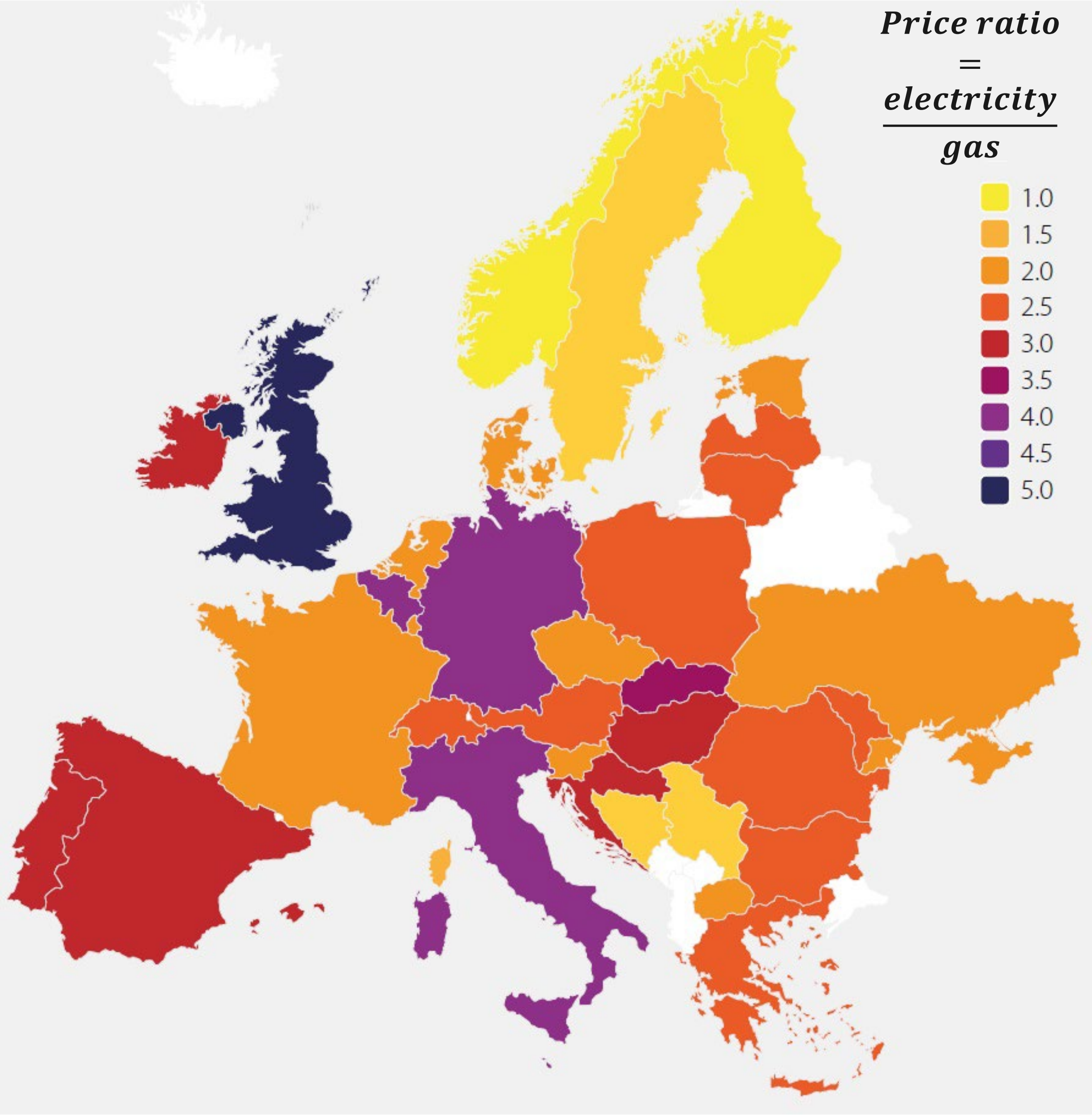
Market Attractiveness depends on Price Ratio between Electricity and Gas

- Decarbonization requires increased use of **renewable electricity**
- **Electricity is more expensive** than fossil fuel in many European countries



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

Source: De Boer et al. (2020): Strengthening Industrial Heat Pump Innovation, Decarbonizing Industrial Heat, White Paper, July 14, 2020

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Steam generating version of the ThermBooster™

SPH Sustainable Process Heat

Image courtesy by SPH Sustainable Process Heat GmbH

- High-temperature 4-cylinder piston compressor (multiple possible)
- Heating capacity: 400 kW to 1 MW (dependinig on operating point)
- Synthetic refrigerants: R1233zd(E), R1336mzz(E), R1336mzz(Z)
- Max. steam pressure: 6 bar(a), 165 °C

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Laboratory for testing the ThermBooster™

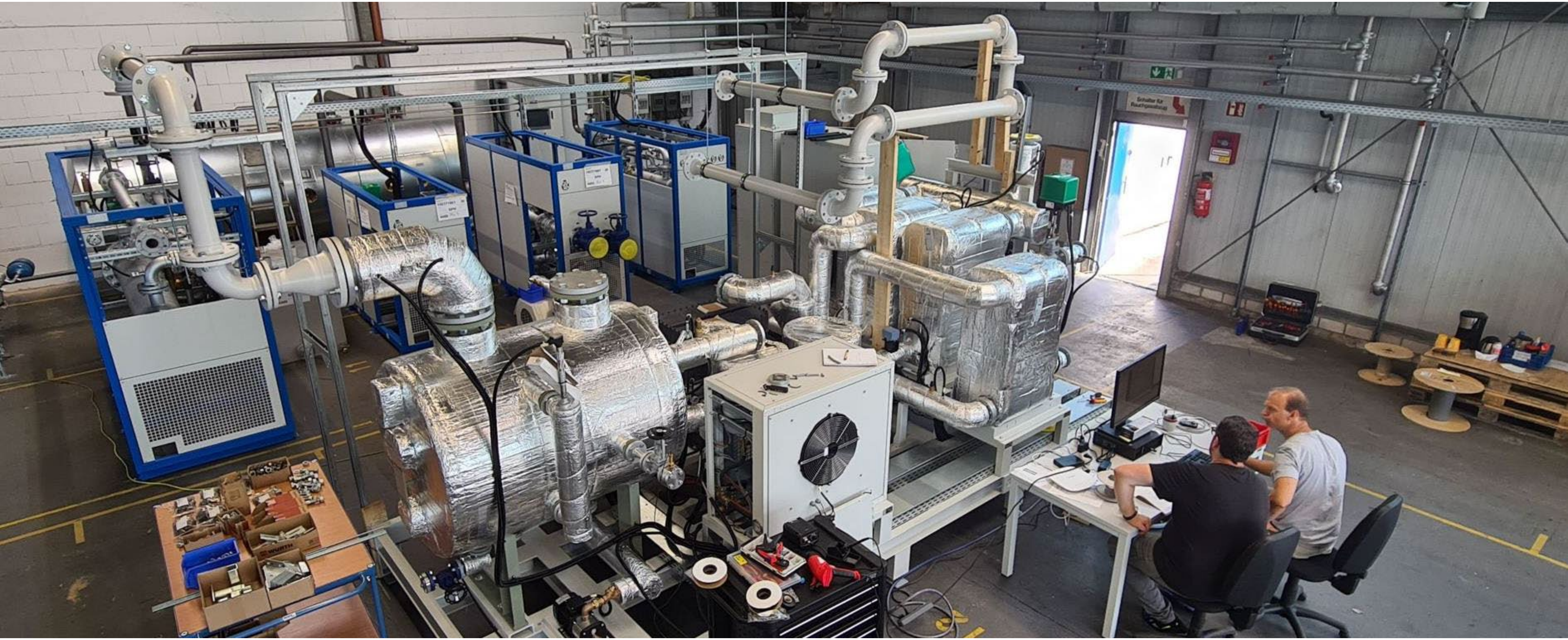

Image courtesy by SPH Sustainable Process Heat GmbH

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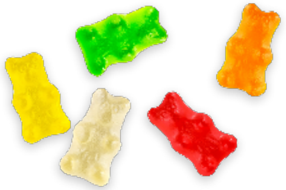
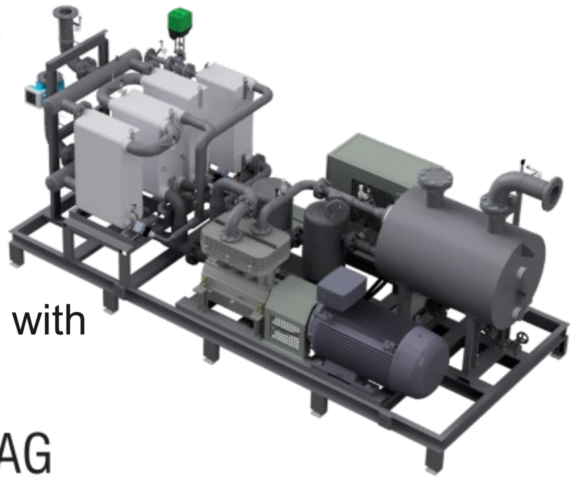
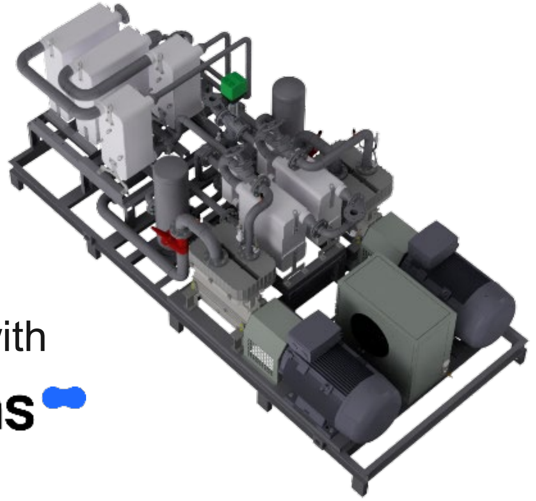
Applications of the ThermBooster™

Application	Gelatine	Thermoplastic from waste
Heat source	85/70 °C	75/65 °C (water)
Heat sink	812 kg/h steam at 2 bar	90/130 °C (hot water) for drying process
Heating capactiy	514 kW	1'017 kW (2 cycles)
Cooling capacity	407 kW	809 kW
Electrical power	118 kW	229 kW (2 compressors)
COP	4.4	4.4
Energy savings	4.1 GWh_{th}/a	1.25 Mio. m^3 gas/a
CO_2 emission reduction	550 t CO_2/a	~2'400 t CO_2/a

In cooperation with 2G Energy AG

In cooperation with technotrans

Image courtesy by SPH Sustainable Process Heat GmbH

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Heaten's 1.5 MW_{th} Very High-Temperature Heat Pump

Image courtesy by Heaten AS

- **HeatBooster HBL4 1.5 MW**
- **20-foot container (5.6 x 2.3 x 2.4 m)**
- **Pilot by the end of May 2023**
- **Supply temperature up to 165 °C**
- Low-pressure steam production
- R1233zd(E) or R1336mzz(Z)
- Hydrocarbons as working fluids
- 50% to 60% Carnot efficiency
- Upon request: 2-stage heat pump cycle design option
- "Scale-up 6 MW_{th} soon" with piston compressors in V-shape

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Heaten's HeatBooster Container Solutions

Images courtesy by Heaten AS

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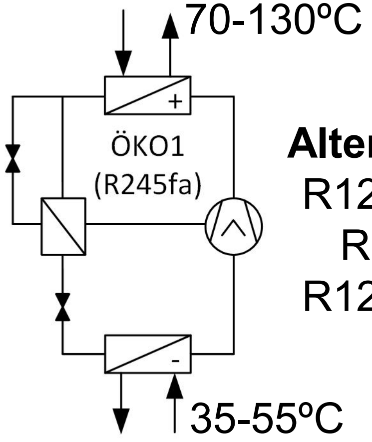
HTHP Case Studies from OCHSNER ENERGIE TECHNIK

IWWDS ER3b (1-stage with economizer)

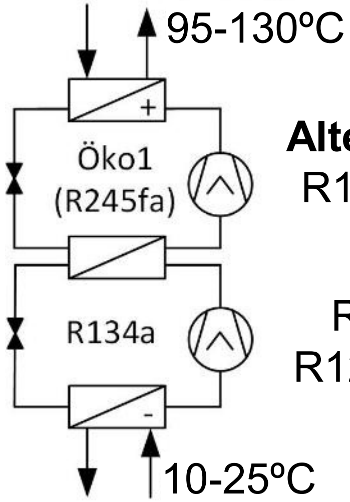
170 to 400 kW



Alternatives:
R1233zd(E)
R513 or
R1234ze(E)

IWWDSS R2R3b (2-stage cascade)

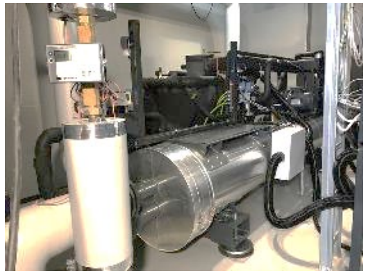
90 to 530 kW



Alternatives:
R1233zd(E)

R513 or
R1234ze(E)

	Mänttä-Vilpula (FIN)	Leather production Couro Azul (POR)
Heat pump type	IWWDS 120 ER3	IWWDS 270 ER4b
Heating Capacity	158 kW	309 kW
Application	**Local district heating network**	**Hot water for production**
Heat Sink	**120 °C**	**120 °C**
Heat Source	45 to 55 °C	55 °C
Source	District heating network return line	Water
Compressor Refrigerant	Screw ÖKO 1 (R245fa)	Screw R1233zd(E)
COP	**2.0**	**2.47**



Images courtesy by OCHSNER Energie Technik GmbH

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Application Examples of HTHPs from Combitherm

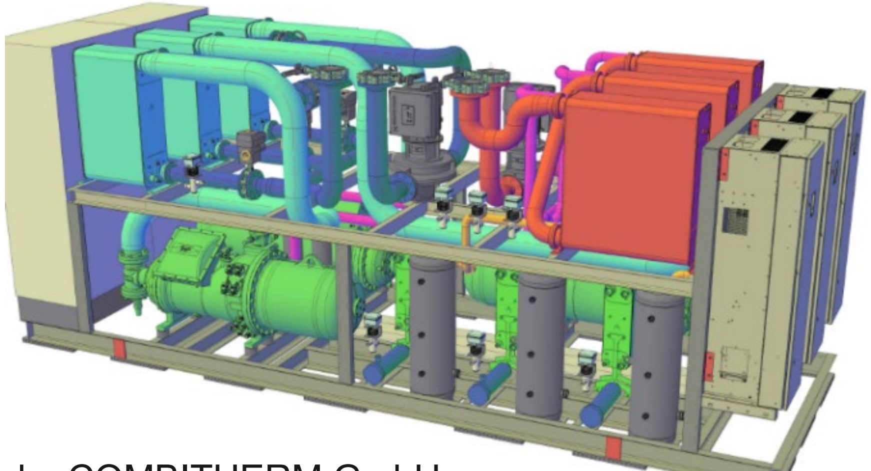
Combitherm
APPARATE- UND ANLAGENBAU

Armstrong

Animal Feed Production
Max. 120 °C (hot water)
2 x 750 kW (heating capacity)
Waste air from dryers
(heat source)

Aqua Feed Production
Max. 120 °C
3.5 MW
Waste air from dryers

HWW 3/9573
Max. 120 °C
1’060 kW
R1233zd(E)



Cleaning Technology
Max. 100 °C
400 kW
Waste heat

Images courtesy by COMBITHERM GmbH

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HoegTemp Ultra High-Temperature heat pump from Enerin AS

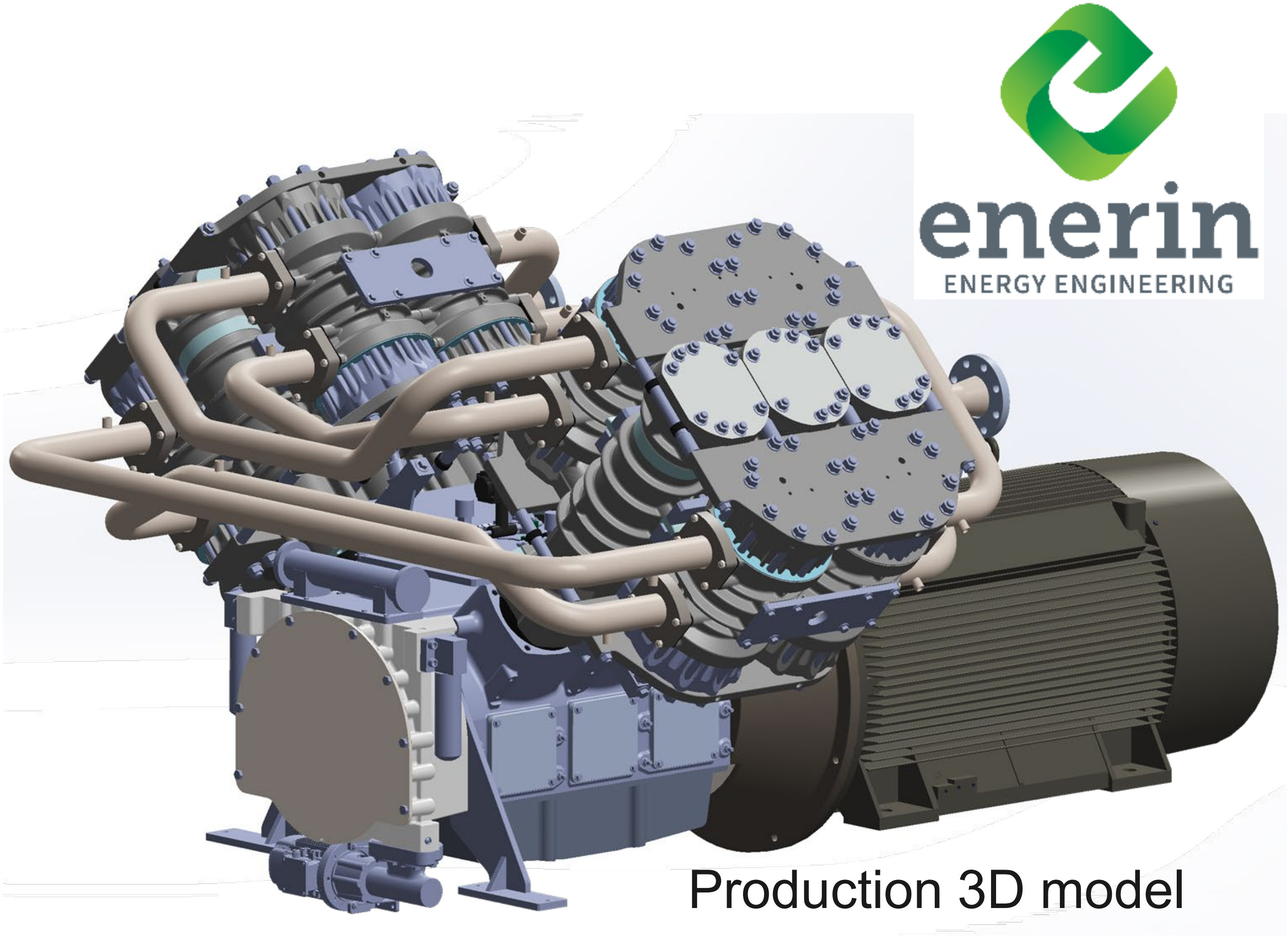

Image courtesy by Enerin AS

- **6-cylinder stirling-cycle heat pump**
- **Double-acting piston compressor**
- **Helium (R704)** refrigerant: zero ODP and GWP
- Heating capacity: 400 kW
- Heat exchangers for heat source and heat sink integrated in compressor assembly
- Patented technology
- 45% Carnot efficiency for high temperature lifts
- More than 30’000 hours of operating experience with prototypes
- 2023: start of commercial deliveries and prototype in biogas facility (10 to 40 °C → 140 to 190 °C)
- 2025: 12-cylinder version (800 kW)

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Illustration of 3.2 MW system with 4 x V12 HoegTemp heat pumps

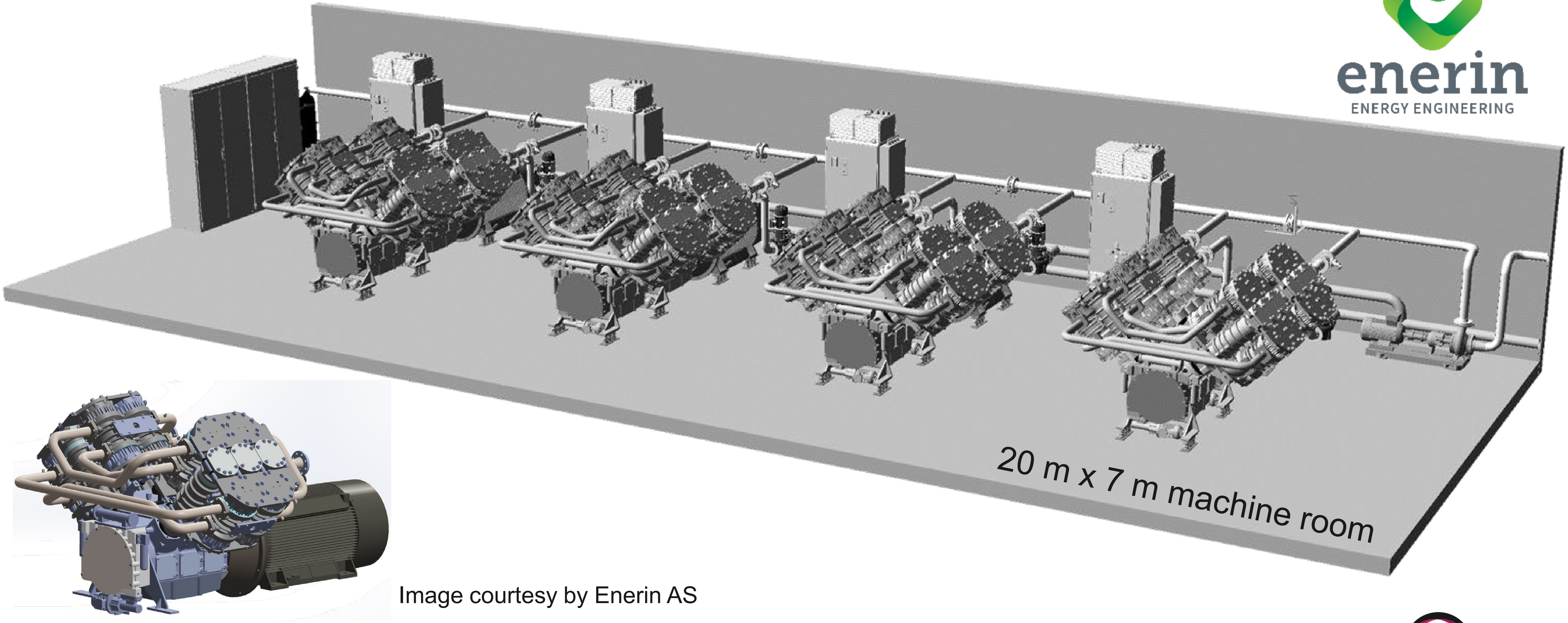

Image courtesy by Enerin AS

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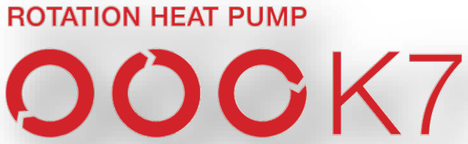
Rotation Heat Pump from ecop Technologies GmbH



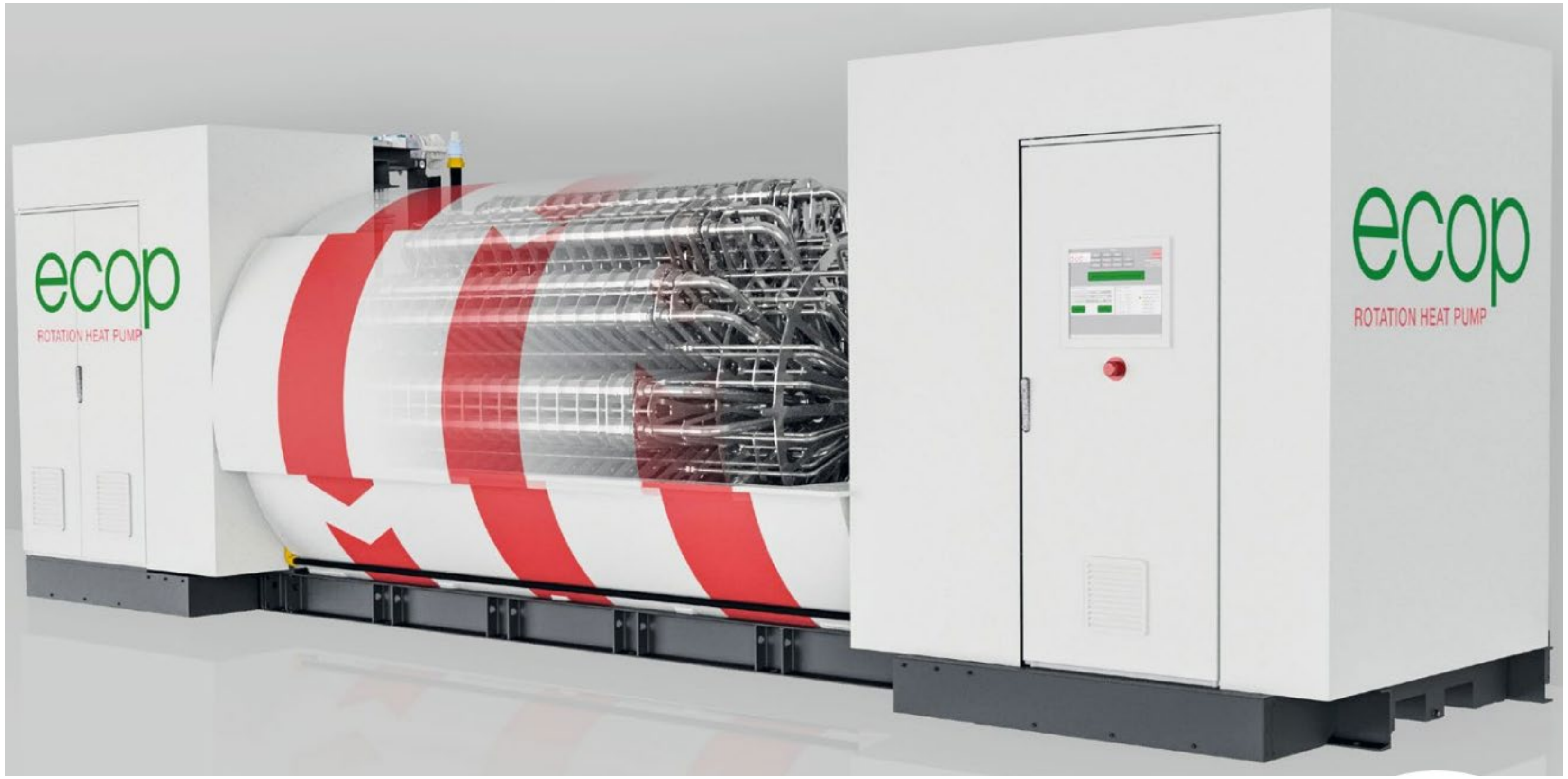


Image courtesy by ecop

- **Joule process**
- **Working fluid: Nobel gas mixture (He, Kr, Ar)**
- **GWP < 1, ODP = 0**
- **Non-toxic, non-flammable**
- **No issue with PFAS or TFA**
- Dimensions: 8.1 x 2.7 x 2.2 m
- Mass: 16 tons
- Heat output: 500 to 700 kW th
- Flexible temperature ranges from 20 °C to 150 °C
- Varible temperature lift up to 55 K from sink outlet to source outlet
- www.ecop.at

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Rotation Heat Pump from ecop Technologies GmbH

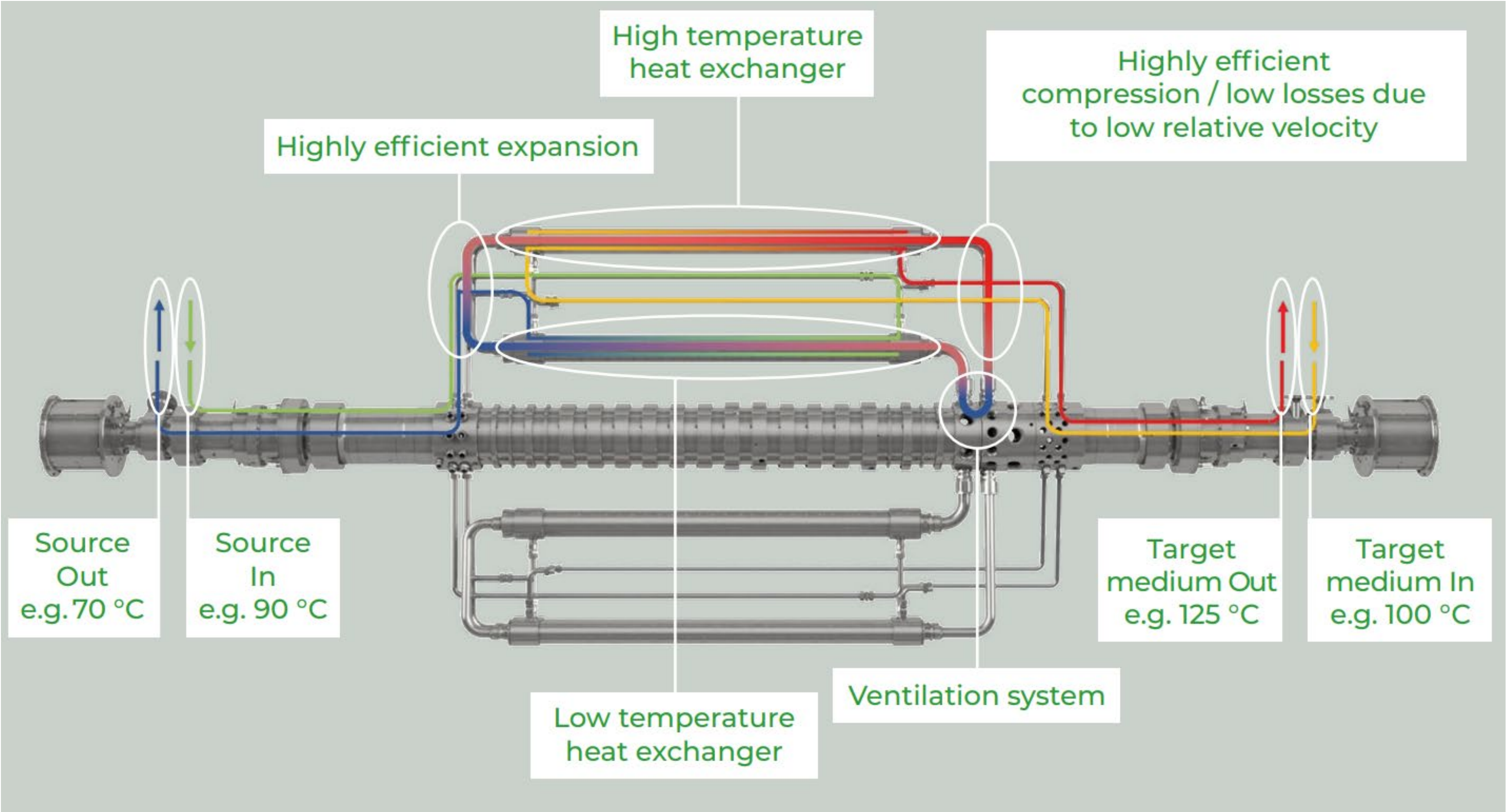

Image courtesy by ecop

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- Varible temperature lift up to 55 K from sink outlet to source outlet
- www.ecop.at

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R717/R600 heat pump for district heating

- **R717 in the bottom cycle (Sabroe HeatPAC) and R600 in top cycle**
- Ventilated in case of leak detection
- Heated ATEX-compliant enclosure to avoid frosting in winter during standstill periods
- Tested and shipped to the client
- Tested with **n-butane (R600) and iso-butane (R600a)**
- FAT test done online
- Final test at site: start of 2023
- COP is 5.7 at 40 °C/90 °C, 500 kW

Image courtesy by Johnson Controls

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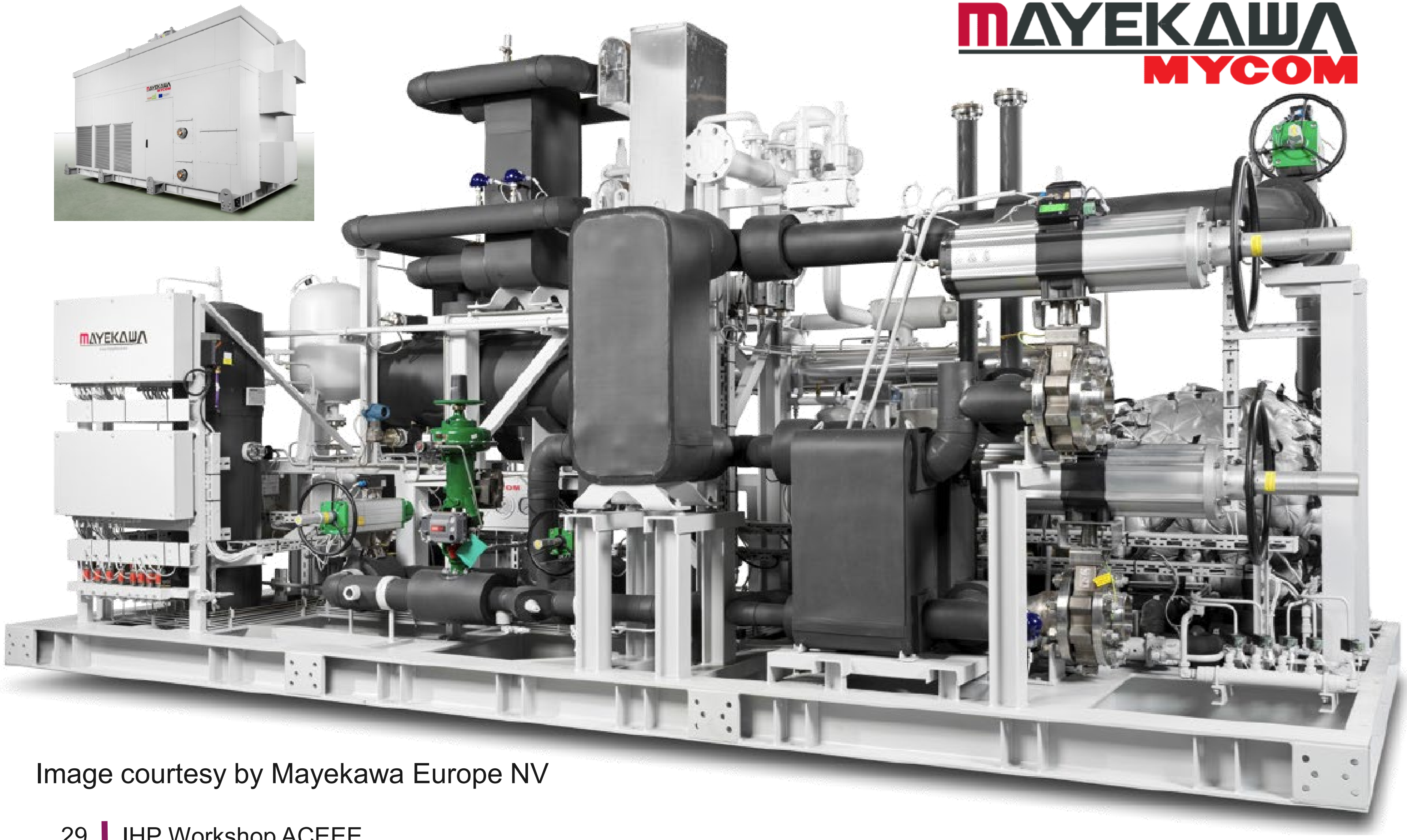
Butane (R600) Heat Pump from Mayekawa Europe NV

MAYEKAWA MYCOM



- Heating capacity around 750 kW
- Reciprocating compressor
- 18 m^2 footprint
- Hot brine up to 120 °C (70 °C inlet) for district heating applications
- Heat source: 72 °C (in), 45 to 65 °C (out)
- COP 3.2 to 4.8

$T_{source,in}$ [°C]	$T_{source,out}$ [°C]	$T_{sink,in}$ [°C]	$T_{sink,out}$ [°C]	$COP_{heating}$ [-]
72	65	70	120	4.8
72	60	70	120	4.4
72	55	70	120	4
72	50	70	120	3.7
72	45	70	120	3.2

Image courtesy by Mayekawa Europe NV

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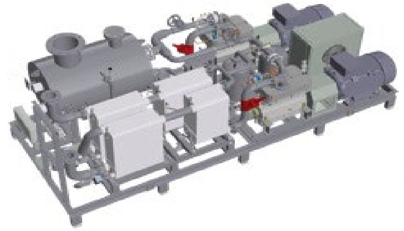
Case studies & demo Sites (www.push2heat.eu)

Push2Heat

Industry sector	Demo 1: Paper	Demo 2: Paper	Demo 3: Chemical	Demo 4: R&D plant
Plant owner	Felix Schoeller Group	Cuartiere di Guarcino	Dynasol	QPinch facilities
Location	Weissenborn, Germany	Lazio, Italy	Santander, Spain	Antwerp, Belgium
HP supplier	SPH	Enertime	BS-Nova	QPinch
Technology	Piston compressor 	Turbo compressor 	Absorption Heat Transformer (H_2O/LiBr) 	Thermochemical Heat Transformer 
Waste heat	35 to 55 °C (exhaust air from paper machine dryer)	85 to 90 °C (cooling water from biomass cogeneration plant)	85 to 90 °C (chemical solvent or steam condensate)	60 to 90 °C
Heat supply	2.2 bara (123 °C) steam	3.3 bara (137 °C) steam 1.8 bara (117 °C) steam	1.0 to 1.5 bara (100 to 111 °C) steam	110 to 150 °C (hot water or steam)
Heat sink capacity	1’180 kW	1.9 MW (high pressure) 0.6 MW (low pressure) 2.1 MW (heat source)	500 to 600 kW 1’300 kW (heat source)	1 MW
Efficiency	Electrical: 2.3	Electrical: 3.6	Thermal: 0.47 Electrical: 60 to 100	Electrical: 25 to 35

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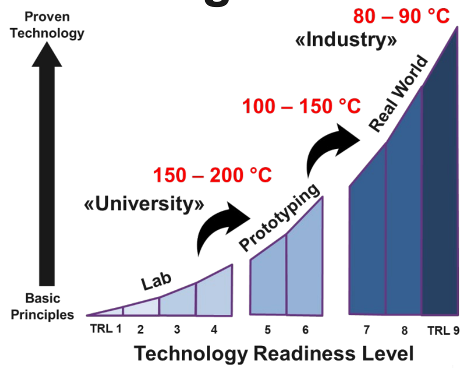
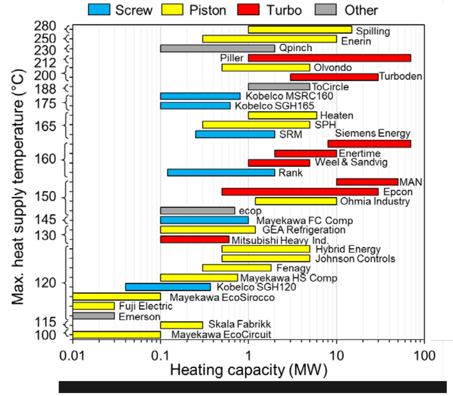
Summary and conclusions

- **Technology status:** HTHP products and technologies with >100 °C supply temperature are increasingly available in Europe (TRL 8 to 9), HTHP innovation is going on → see IEA HPT Annex 58 Overview

IEA HPT



- **Application examples**: Various realized references, demonstration projects, case studies, and many potential applications (e.g., pressurized water, hot air for drying processes, low-pressure steam)

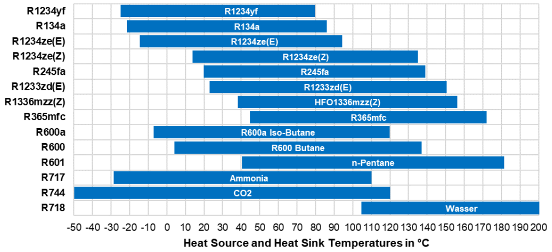


- **Market attractiveness:** Depends on electricity to gas price ratio and COP (temperature lift), favorable countries
- **Significant energy savings and CO_2 emission reductions** are possible
- **Refrigerant issues:** The impact of new European regulations (F-gas, PFAS, TFA) on the US market is not clear, there is a trend towards natural refrigerants (e.g., H_2O, CO_2, NH_3, helium, hydrocarbons) and synthetic HFOs with low GWP

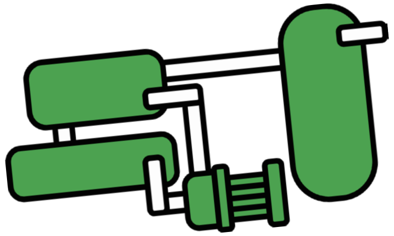
HOT WATER

HOT AIR

STEAM



Have confidence in HTHP and give the HTHP technology a try!



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Acknowledgements

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office of Energy SFOE

Project: Annex 58 HTHP-CH
Integration of High-Temperature Heat Pumps (HTHPs) in Swiss Industrial Processes
(SI/502336-01)

sweet swiss energy research for the energy transition
DeCarbCH
DeCarbonisation of Cooling and Heating in Switzerland
www.sweet-decarb.ch

Push2Heat
Pushing forward the market potential of heat upgrading technologies in the industrial sector

Funded by the European Union

Grant Agreement No. 101069689
https://push2heat.eu

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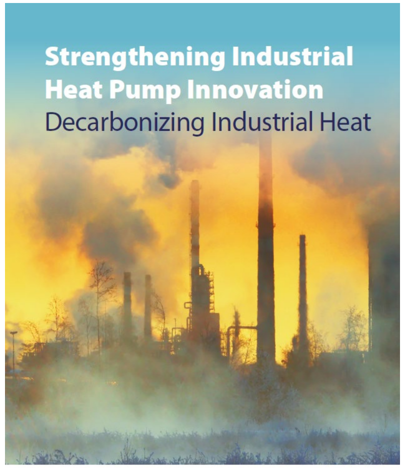
Literature References



Arpagaus, C.; Bless, F.; Bertsch, S.: Techno-Economic Analysis of Steam-Generating Heat Pumps in Distillation Processes, 3rd High-Temperature Heat Pump Symposium 2022, 29-30 March 2022, Copenhagen, Denmark

Mateu-Royo, C.; Arpagaus, C.; Mota-Babiloni, A.; Navarro-Esbrí, J.; Bertsch, S.: Advanced High Temperature Heat Pump Configurations using low GWP Refrigerants for Industrial Waste Heat Recovery: A Comprehensive Study, Energy Conversion and Management, Vol. 229, 1 February 2021, 113752, https://doi.org/10.1016/j.enconman.2020.113752

Kosmadakis, G.; Arpagaus, C.; Neofytou, P.; Bertsch, S.: Techno-Economic Analysis of High-Temperature Heat Pumps with low-GWP Refrigerants for upgrading Waste Heat up to 150 °C, Energy Conversion and Management, Vol. 226, 113488, pp. 1-19, https://doi.org/10.1016/j.enconman.2020.113488

Schiffmann, J.; Kontomaris, K.; Arpagaus, C.; Bless, F.; Bertsch, S.: Scale Limitations of Gas Bearing Supported Turbocompressors for Vapor Compression Cycles, International Journal of Refrigeration, Vol. 109, pp. 92-104, 2020, https://doi.org/10.1016/j.ijrefrig.2019.09.019

Schlosser, F.; Jesper, M.; Vogelsang, J.; Walmsley, T.G.; Arpagaus, C.; Hesselbach, J.: Large-Scale Heat Pumps: Applications, Performance, Economic Feasibility and Industrial integration, Renewable and Sustainable Energy Reviews, Vol. 133, 1102019, pp. 1-20, 2020, https://doi.org/10.1016/j.rser.2020.110219

Arpagaus, C.; Bertsch, S.: Industrial Heat Pumps in Switzerland – Application Potentials and Case Studies, Final Report, on behalf of the Swiss Federal Office of Energy, SFOE contract number: SI/501782-01, Bern, 23 July 2020.

De Boer, R.; Marina, A.; Zühlsdorf, B.; Arpagaus, C.; Bantle, M.; Wilk, V.; Elmegaard, B.; Corberán, J.; Benson, J.: Strengthening Industrial Heat Pump Innovation, Decarbonizing Industrial Heat, White Paper, 14 July 2020.

Arpagaus, C.; Bertsch, S.: Experimental Comparison of R1224yd(Z) and R1233zd(E) in a High Temperature Heat Pump, 13th IEA Heat Pump Conference, Jeju, Korea, 26-29 April 2021.

Arpagaus, C.; Bertsch, S.: Successful Application Examples of Industrial Heat Pumps in Switzerland, IIR International Rankine 2020 Conference, 27-31 July 2020, Glasgow, UK, https://doi.org/10.18462/iir.rankine.2020.1183

Arpagaus, C.; Bertsch, S.: Experimental Comparison of HCFO R1233zd(E) and R1224yd(Z) in a High Temperature Heat Pump up to 150 °C, IIR International Rankine 2020 Conference, 27 to 31 July 2020, Glasgow, UK, https://doi.org/10.18462/iir.rankine.2020.1129

Arpagaus, C.; Bertsch, S.: Experimental Comparison of HCFO and HFO R1224yd(Z), R1233zd(E), R1336mzz(Z), and HFC R245fa in a High Temperature Heat Pump up to 150 °C Supply Temperature, 18th International Refrigeration and Air Conditioning Conference at Purdue, 23-27 May 2021.

Arpagaus, C.; Bless, F.; Bertsch, S.: Theoretical Analysis of Transcritical HTHP Cycles with low GWP HFO Refrigerants and Hydrocarbons for Process Heat Applications up to 200 °C, IIR International Rankine 2020 Conference, 27-31 July 2020, Glasgow, UK, https://doi.org/10.18462/iir.rankine.2020.1168

Bless, F.; Arpagaus, C.; Bertsch, S.: Theoretical Investigation of High-Temperature Heat Pump Cycles for Steam Generation, 13th IEA Heat Pump Conference, Jeju, Korea, 26 -29 April 2021.

Diewald, K; Arpagaus, C.; Hebenstreit, B.: Thermodynamic Analysis of low GWP HFO and HCFO Refrigerants in HTHP with Large Temperature Glides on the Heat Sink, IIR International Rankine 2020 Conference, 27-31 July 2020, Glasgow, UK, https://doi.org/10.18462/iir.rankine.2020.1166

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Backup Slides

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Europe EU-28 – Industrial sectors

	Heat Consumption (TWh/a)	EU-28	
	Space heating	297	16%
	Hot water	25	1%
Process heat	PH <60 °C	55	3%
Process heat	PH 60 to 80 °C	53	3%
Process heat	PH 80 to 100 °C	**89**	**5%**
Process heat	PH 100 to 150 °C	**192**	**11%**
Process heat	PH 150 to 200 °C	**80**	**4%**
Process heat	PH 200 to 500 °C	151	8%
Process heat	PH 500 to 1'000 °C	376	21%
Process heat	PH >1'000 °C	504	28%
	Total Heat Consumption (TWh/year)	1'821	100%

Process Heat Consumption (TWh/a)		
Industrial sector	**PH 100 to 150 °C**	**PH 150 to 200 °C**
Iron and steel	19.8	7.3
Chemical	19.3	15.4
Non-ferrous metal	2.7	1.0
Non-metallic minerals	36.5	0.0
Food and tobacco	68.0	8.8
Paper, pulp and print	10.0	39.4
Machinery	6.9	2.9
Wood and wood products	0.2	0.7
Transport equipment	1.2	0.2
Textile and leather	6.9	0.0
Other	19.1	4.2
Total	**191**	**80**

Data: Kosmadakis (2019): Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries, Applied Thermal Engineering, 156, 287-298, https://doi.org/10.1016/j.applthermaleng.2019.04.082

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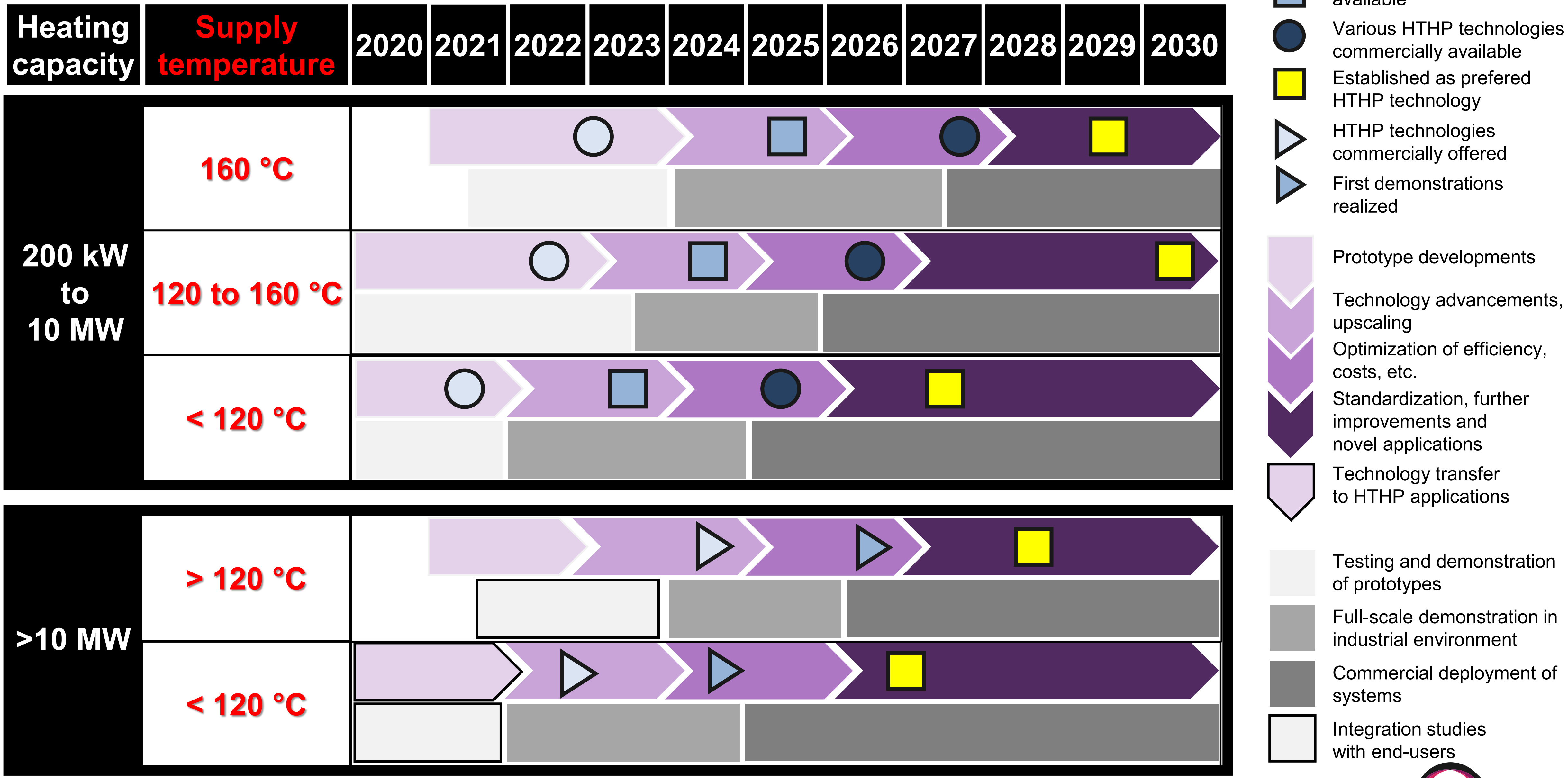
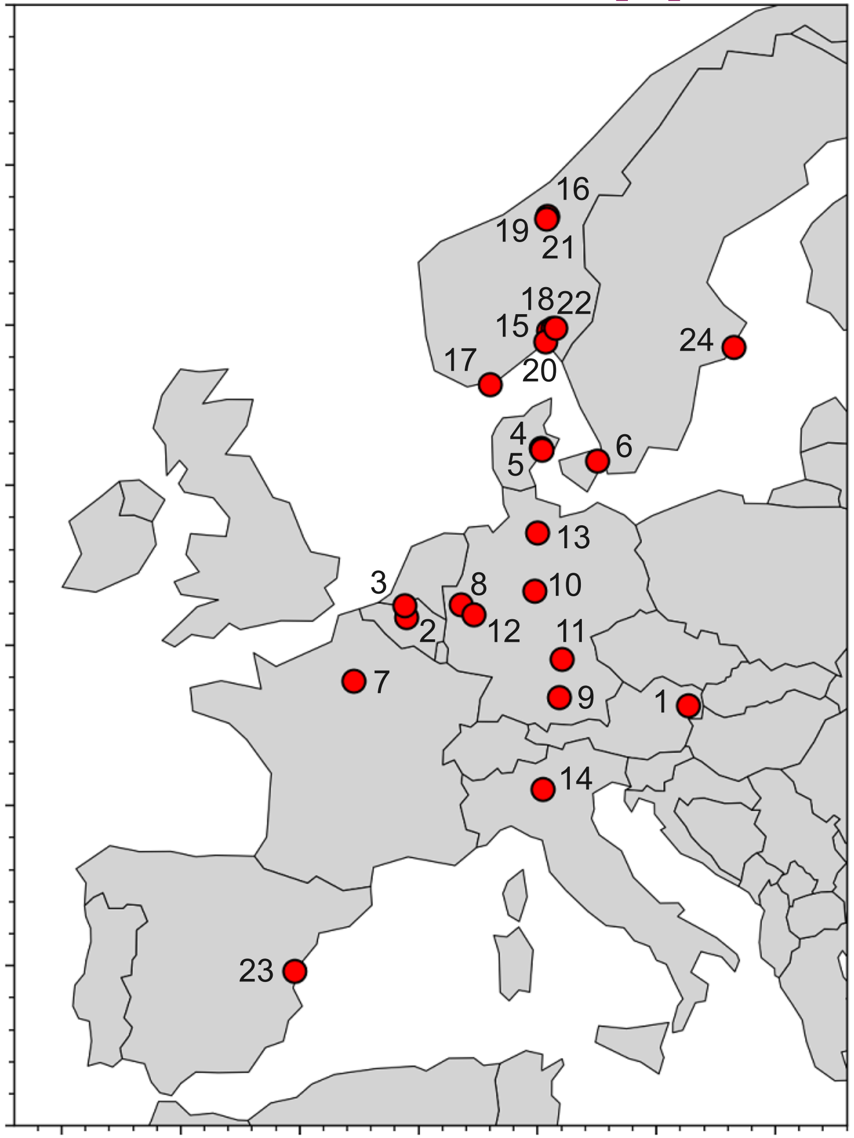
Potential HTHP Development Perspectives until 2030



Headquarters of HTHP suppliers in Europe



1	Ecop (AT)
2	Mayekawa MYCOM (BE)
3	Qpinch (BE)
4	Fenagy (DK)
5	Johnson Controls (DK)
6	Weel and Sandvig (DK)
7	Enertime (FR)
8	GEA (DE)
9	MAN (DE)
10	Piller (DE)
11	Siemens (DE)
12	SPH (DE)
13	Spilling (DE)
14	Turboden (IT)
15	Enerin (NO)
16	Epcon (NO)
17	Heaten (NO)
18	Hybrid Energy (NO)
19	Ohmia (NO)
20	Olvondo (NO)
21	Skala Fabrikk (NO)
22	ToCircle (NO)
23	Rank (ES)
24	SRM (SE)

Japan

25	Fuji (JP)
26	KOBELCO (JP)
27	Mitsubishi (JP)

Based on database of IEA HPT Annex 58:
https://heatpumpingtechnologies.org/annex58/task1

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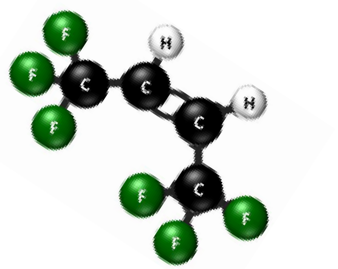
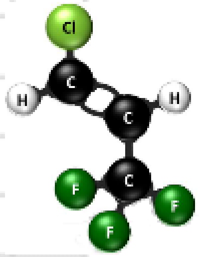
Commercial High-Temperature Heat Pumps for Supply Temperatures > 100 °C

Suitable refrigerants for HTHPs

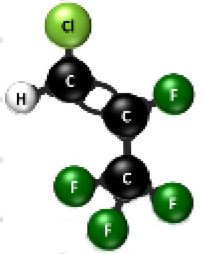
Selection criteria :
- Low GWP
- Short atm. lifetime
- Zero/low ODP
- Low flammability
- High efficiency
- High T_{crit}



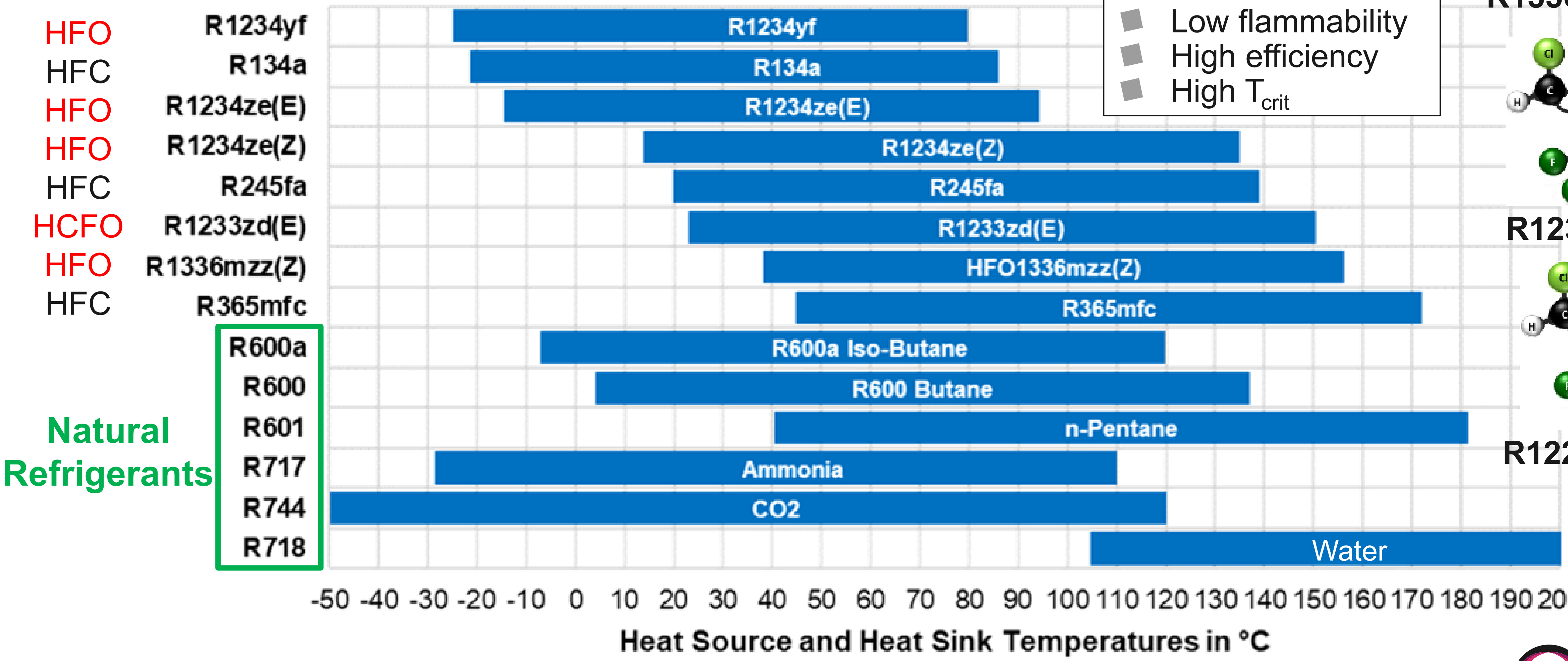
R1336mzz(Z)



R1233zd(E)



R1224yd(Z)



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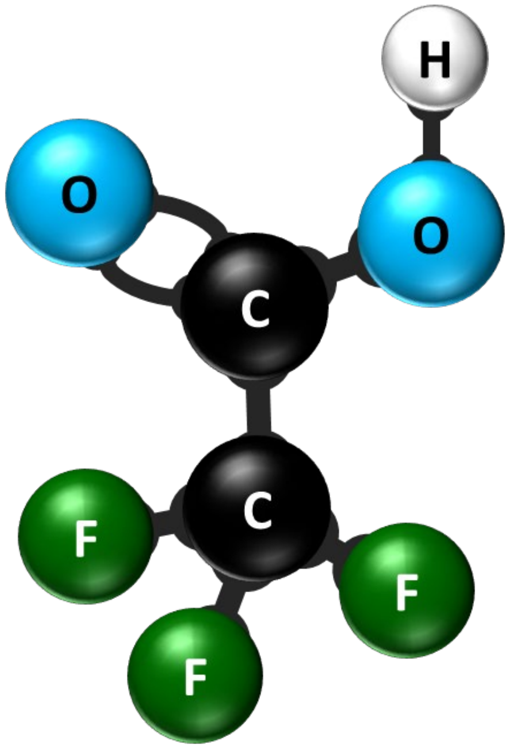
Formation of trifluoroacetic acid (TFA, CF_3COOH)

Trifluoroacetic acid (TFA)
CF_3-C(O)OH



- TFA is an end product of atmospheric degradation of halogenated refrigerants
- Persistent in the environment and also mobile in the aquatic environment
- TFA can basically be formed from various substances, the presence of a **CF_3-CF= group** is considered a prerequisite for TFA formation

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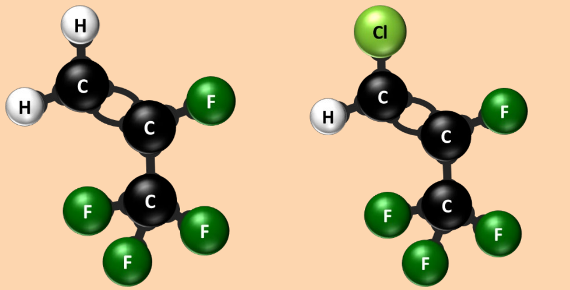
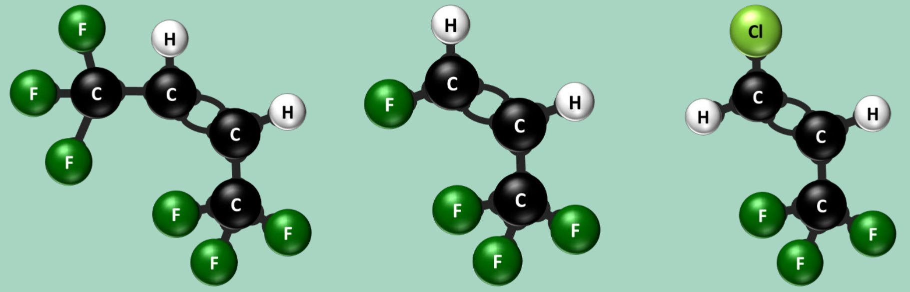
Molar yield of TFA during atmospheric degradation of HFOs



R1234yf
CF_3-CF=CH_2

R1224yd(Z) [1]
Z-**CF_3-CF**=CHCl

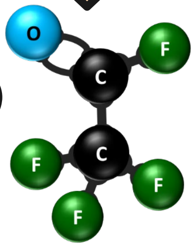


R1336mzz(Z) [2]
Z-**CF_3-CH**=$CHCF_3$

R1234ze(Z)
Z-**CF_3-CH**=CHF

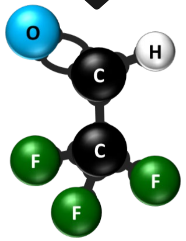
R1233zd(E) [3]
E-**CF_3-CH**=CHCl

CF_3-CF=
group



Trifluoracetyl fluoride (TFF)
CF_3-C(O)F

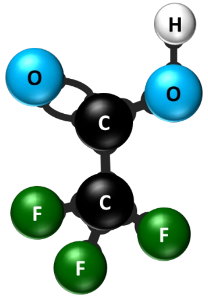
CF_3-CH=
group



Trifluoracetaldehyde
CF_3-C(O)H

[1] 97%
(Guo et al., 2019)

~ 100%



Trifluoroacetic acid (TFA)
CF_3-C(O)OH

< 10%

[2] < 20%, because of 2 x CF_3-CH=
(Henne et al., 2012)
[3] ~2% (Sulbaek Andersen et al., 2018)

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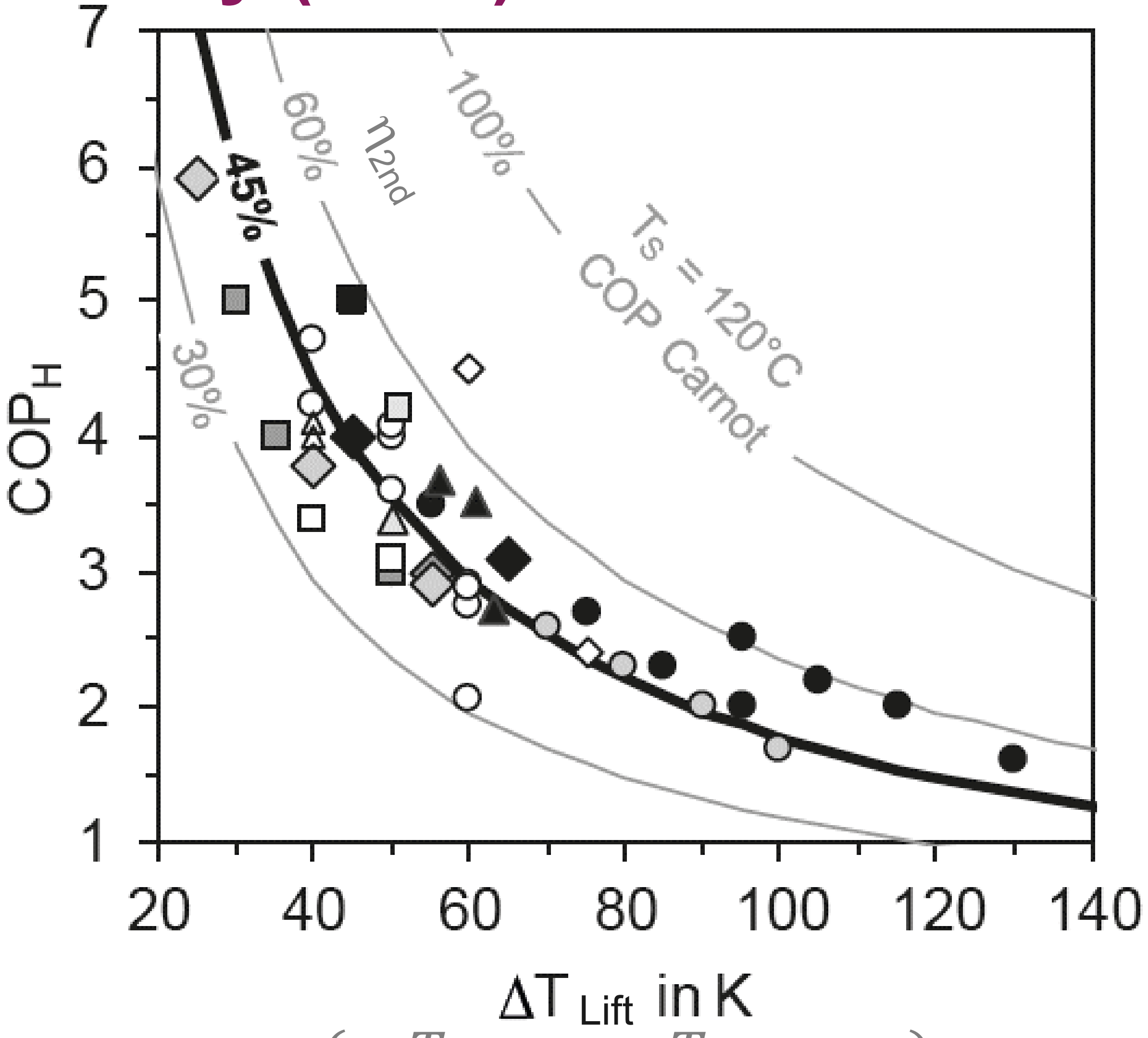
Efficiency (COP) of industrial heat pumps



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

COP Fit-curve
(45% 2nd Law efficiency)

$$COP_H = 68.455 \cdot \Delta T_{Lift}^{-0.76}$$

ΔT_{Lift}	COP_H
30 K	5.2
40 K	4.1
50 K	3.5
60 K	3.0
70 K	2.7
80 K	2.4

Source: Arpagaus C., Bless F., Uhlmann M., Schiffmann J, Bertsch S.S. (2018): Review on High-Temperature Heat Pumps, https://doi.org/10.1016/j.energy.2018.03.166

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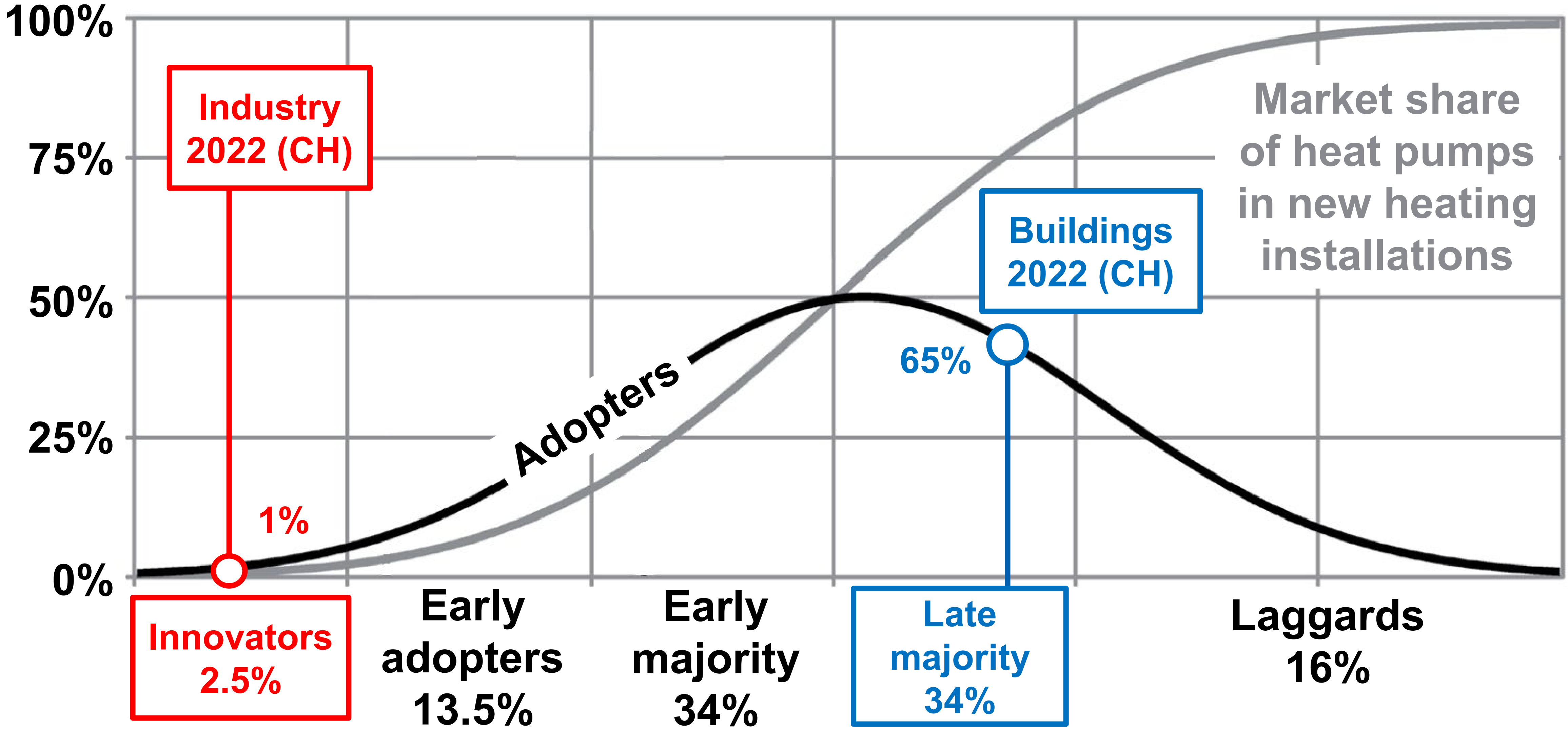
Market Analysis – Diffusion of Innovation

Technology Adoption of Heat Pumps in Switzerland – Status 2022



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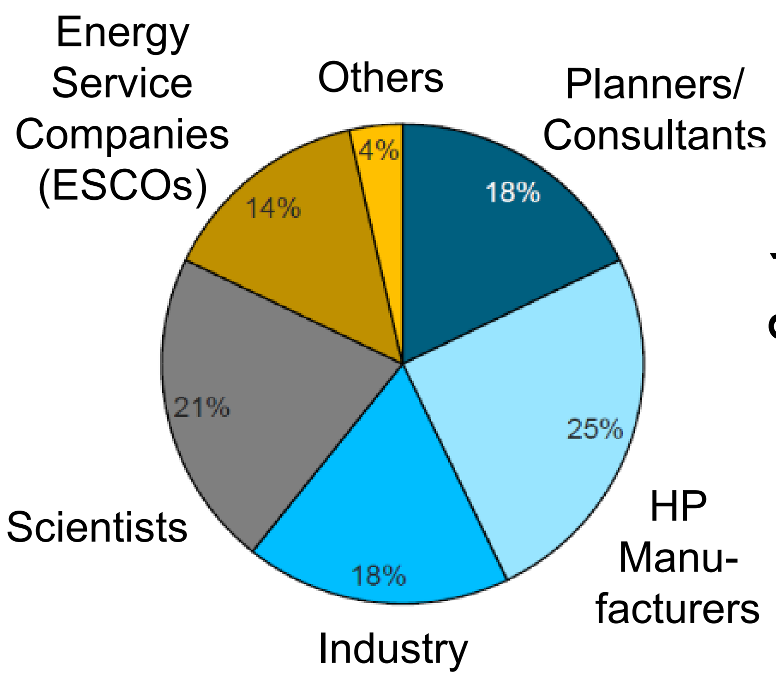
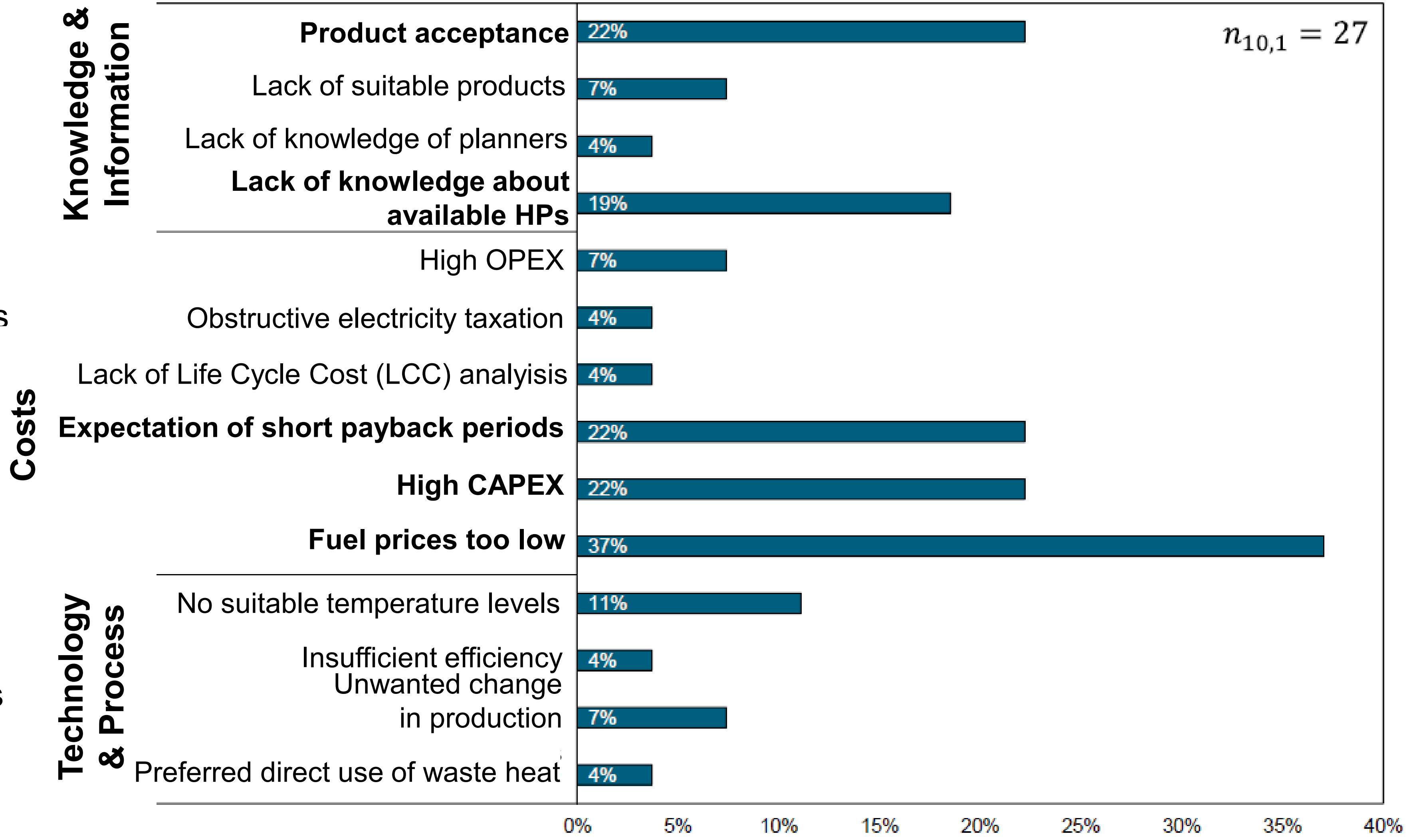
Market Barriers for Industrial Heat Pumps

Survey among 27 experts on heat pumps and heat recovery





Adapted from Wolf et al. (2017): Systematische Anwendung von Großwärmepumpen in der Schweizer Industrie, Endbericht, 10. Mai 2017 and Wolf (2020): Rahmenbedingungen und Märkte für Industriewärmepumpen, ETV Online Tagung 2020, Industrielle Gross- und Hochtemperaturwärmepumpen im Energiesystem, 22. Juli 2020

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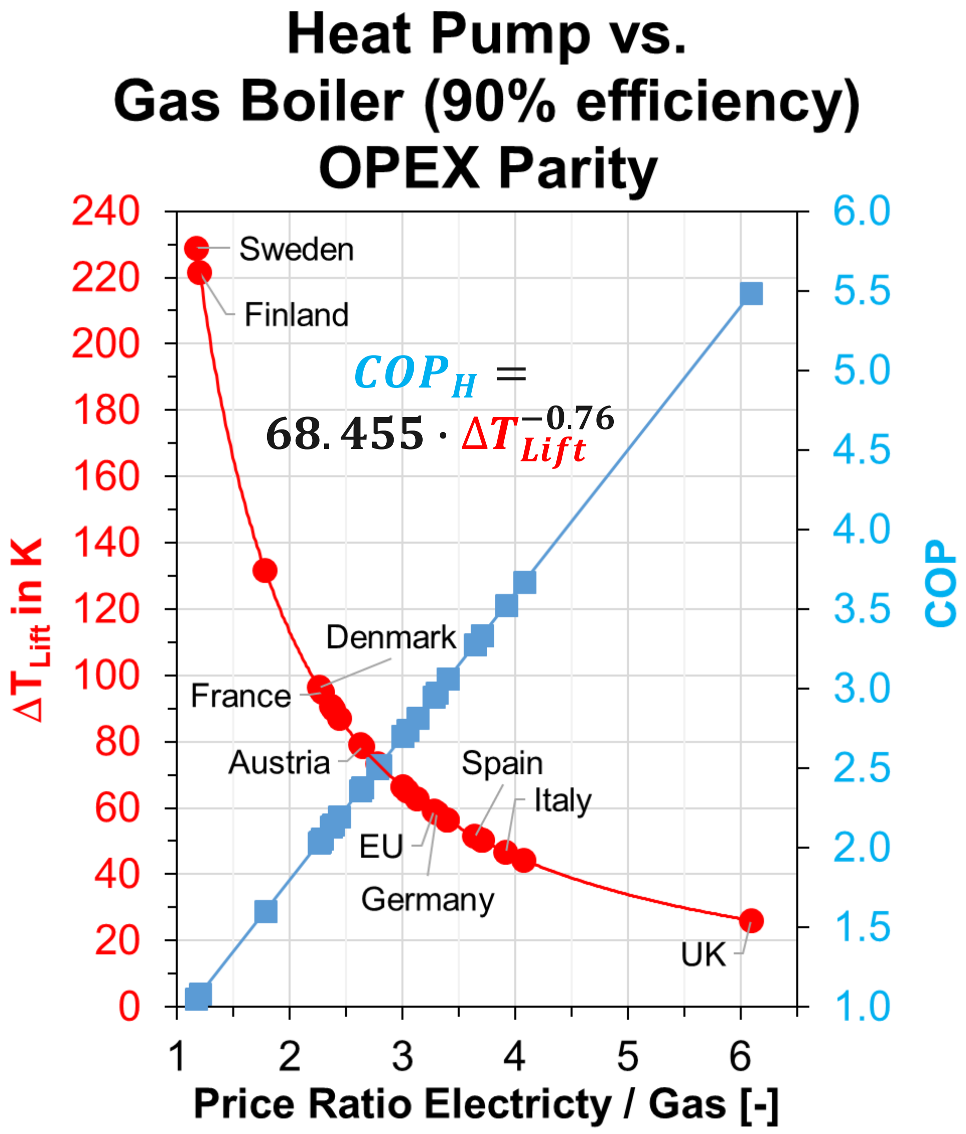
OPEX Parity COP and Temperature Lift

$$COP = \frac{Price_{Electricity}}{Price_{Gas}} \cdot \eta_{Gas\ Boiler}$$

90%

Country	Prices without refundable Gas	Electricity	Price Ratio	OPEX Parity COP	ΔT_Lift
Sweden	**4.1**	**4.8**	**1.17**	**1.1**	**229**
Finland	**4.5**	**5.4**	**1.20**	**1.1**	**222**
Luxembourg	2.3	4.1	1.78	1.6	132
Lithuania	3.0	6.8	2.27	2.0	96
Denmark	**3.1**	**7.0**	**2.26**	**2.0**	**96**
France	**2.8**	**6.4**	**2.29**	**2.1**	**95**
Netherlands	2.6	6.2	2.38	2.1	90
Slovenia	2.5	6.1	2.44	2.2	87
Estonia	3.0	7.1	2.37	2.1	91
Czech Republic	2.4	6.3	2.63	2.4	79
Austria	**2.8**	**7.4**	**2.64**	**2.4**	**78**
Latvia	2.7	7.5	2.78	2.5	73
Hungary	2.5	7.0	2.80	2.5	73
Greece	2.5	7.5	3.00	2.7	66
Poland	2.4	7.2	3.00	2.7	66
Romania	2.3	7.0	3.04	2.7	65
Croatia	2.3	7.2	3.13	2.8	63
Belgium	2.0	6.8	3.40	3.1	56
Germany	**2.6**	**8.6**	**3.31**	**3.0**	**58**
Bulgaria	2.0	6.8	3.40	3.1	56
Spain	**2.5**	**9.1**	**3.64**	**3.3**	**51**
Portugal	2.4	8.9	3.71	3.3	50
Ireland	2.7	10.0	3.70	3.3	50
Italy	**2.4**	**9.4**	**3.92**	**3.5**	**47**
Slovakia	2.5	10.2	4.08	3.7	44
UK	**2.1**	**12.8**	**6.10**	**5.5**	**26**
EU	**2.5**	**8.2**	**3.28**	**3.0**	**59**

Market Attractiveness



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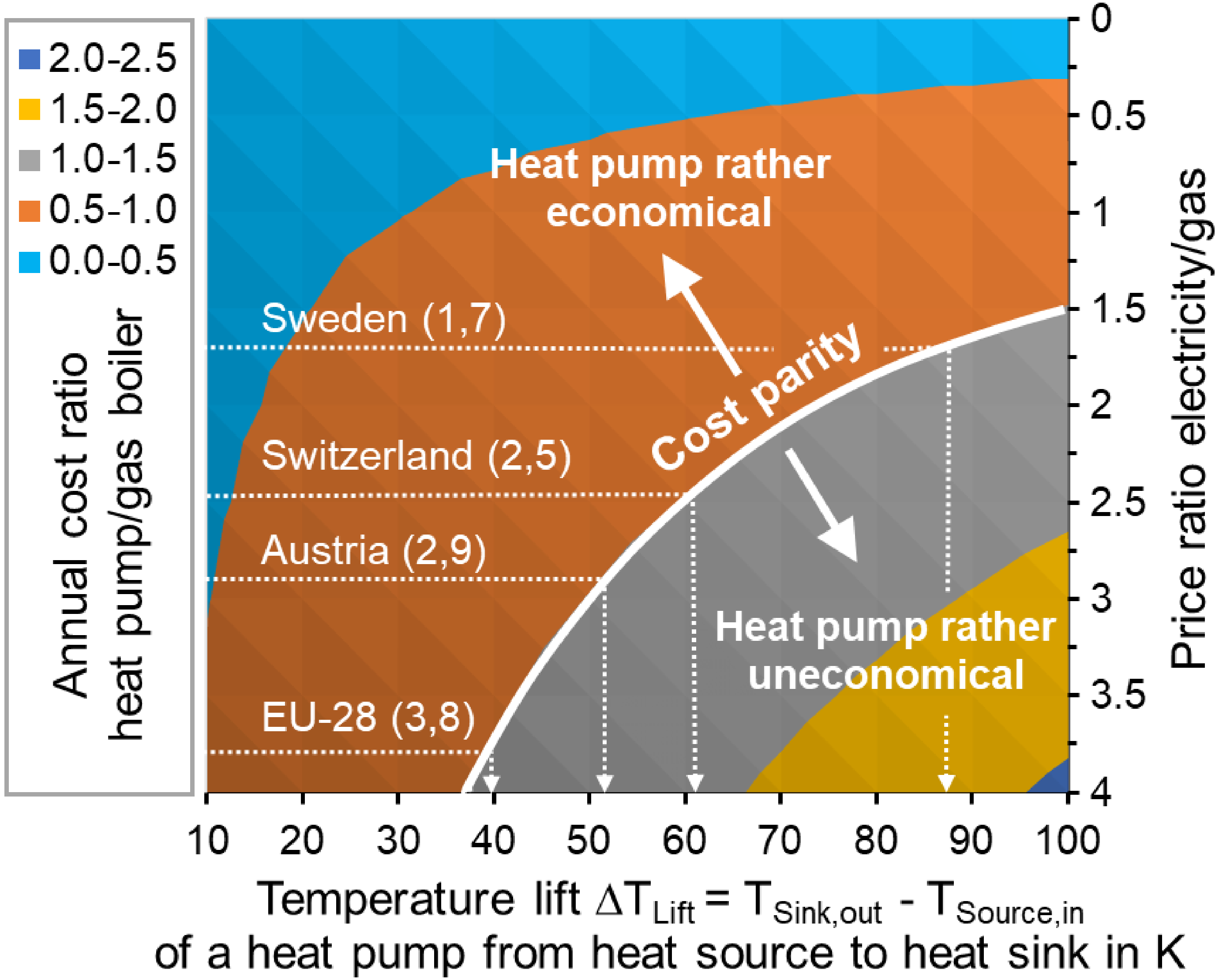
Heat pump integration in comparison to a gas boiler



The marked line shows the cost parity between the annual costs with a heat pump and a gas boiler

Assumptions:	**Heat pump**	**Gas boiler**
Investment costs:	420 EUR/kW	60 Euro/kW
Interest on capital:	5%	5%
Useful life:	15 years	15 years
Annuity:	40.5 EUR/kW	5.8 EUR/kW
Maintenance costs:	2.5%	3% (Investition)
	15 EUR/kW	4,2 EUR/kW
2nd law efficiency (η_{HP}):[1)	45%	
Gas boiler efficiency (η_{Boiler}):		80%
Operating hours:[2)	3'504 h/year	3'504 h/year
Gas price:[3)		0,0301 Euro/kWh

[1) $COP_H = \eta_{HP} \cdot T_{Sink,out} / \Delta T_{Lift}$; $T_{Sink,out}$ = 393,15 (120°C)
[2) 40% x 365 days x 24 h = 3'504 h
[3) Eurostat, EU-28, 2016

Source: Arpagaus (2019): Hochtemperatur Wärmepumpen, Book, VDE Verlag, ISBN 978-3-8007-4550-0, E-Book: ISBN 978-3-8007-4551-7

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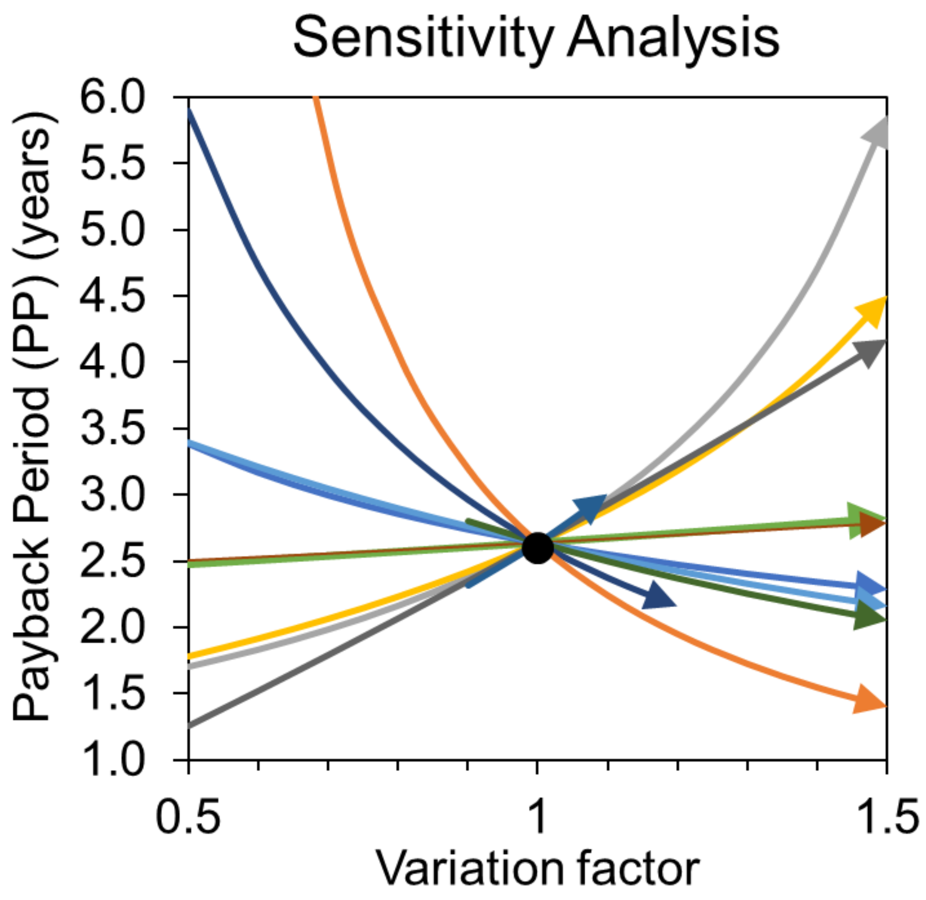
Economic Evaluation – Sensitivity analysis

Payback period for a reference case at 45 °C/115 °C (heat source/sink) and 1 MW heating capacity



	-	Ref	+	
Electricity price (PP ↑)	0.05	**0.10**	0.15	EUR/kWh
Temperature lift	35	**70**	105	K
Cost factor planning & integration	1.0	**2.0**	3.0	-
Efficiency of fuel boiler	0.85	**0.90**	0.95	-
CO_2 emissions factor of electricity	0.064	**0.128**	0.192	$kgCO_2/kWh$
Maintenance factor	0.02	**0.04**	0.06	-
Heating capacity	500	**1'000**	1'500	kW
CO_2 tax	46	**92.5**	139	EUR/tCO_2
CO_2 emissions factor of fuel	0.181	**0.201**	0.302	$kgCO_2/kWh$
Annual operating time	3'600	**7'200**	8'640	h/a
Fuel price (gas, oil) (PP ↓)	0.029	**0.057**	0.086	EUR/kWh
● **Reference Case (Ref)**	-	Variation	+	

1'000 kW, 45 °C/115 °C (Heat source/sink), COP = 2.53
PP = 2.6 years, DPP = 3.2 years

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