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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- Dr. Frédéric Bless
- Michael Uhlmann, Ing.
- Prof. Stefan Bertsch, PhD
Industrial Heat Pumps: Technology readiness, economic conditions, and sustainable refrigerants

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
Motivation

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

Heat pump driven

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

Environment

- Ambient air
- Geothermal heat
- Lake / River
- Solar heat

Potential heat sources

Other industries

Power plants

District heating network

Waste incineration plants

Cooling process

Process cooling

Refrigeration cycle

Electricity

Waste heat

Process heat

High-temp heat pump

Process

Waste heat

Other industries

Power plants

District heating network

Waste incineration plants

Environment

- Ambient air
- Geothermal heat
- Lake / River
- Solar heat

Potential heat sources

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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 °C (730 TWh/a)

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

Total energy demand - 2950 TWh/a

- Process heating (66 %)
- Space heating (11 %)
- Space cooling (1 %)
- Process cooling (3 %)
- Non-thermal (19 %)

Process heating demand - 1952 TWh/a

- > 500°C (52 %)
- 200°C - 500°C (11 %)
- 100°C - 200°C (26 %)
- < 100°C (11 %)

Research to prove feasibility

Develop and demonstrate

Deploy

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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 °C is estimated to be 212 TWh/a (764 PJ/a) (EU28)
- … but still, the **actual market of industrial heat pumps** is emerging

## Temperature levels of industrial processes

### Motivation: Potential applications

### 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](https://doi.org/10.1016/j.energy.2018.03.166)
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

Technology Readiness: HTHP Technologies

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

Technology Readiness: HTHP Technologies

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)
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)

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.

<table>
<thead>
<tr>
<th>HTHP supplier (High-Temperature Heat Pump)</th>
<th>Product</th>
<th>Max. heating capacity (MW)</th>
<th>Max. supply temp. (°C)</th>
<th>TRL (Technology Readiness Level)</th>
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<tbody>
<tr>
<td>Spilling</td>
<td>Steam Compressor</td>
<td>15</td>
<td>280</td>
<td>9</td>
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<tr>
<td>Enerin</td>
<td>HoegTemp</td>
<td>10</td>
<td>250</td>
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<td>Qpinch</td>
<td>Heat Transformer</td>
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<td>230</td>
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<td>Piller</td>
<td>VapoFan</td>
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<td>212</td>
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<td>LHP</td>
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<td>TC-C920</td>
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<td>188</td>
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<td>0.62</td>
<td>175</td>
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<td>Heaten</td>
<td>HeatBooster</td>
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<td>165</td>
<td>7 8 9</td>
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<td>Thermbooster</td>
<td>5</td>
<td>165</td>
<td>7 8 9</td>
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<tr>
<td>SRM</td>
<td>Compressor for water vapor</td>
<td>2</td>
<td>165</td>
<td>7 8 9</td>
</tr>
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<td>Siemens Energy</td>
<td>Industrial Heat Pump</td>
<td>70</td>
<td>160</td>
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<td>HTHPs</td>
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<td>160</td>
<td>5 6 7 8 9</td>
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<td>Rank</td>
<td>Rank® HP</td>
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<td>ETES CO₂ Heat Pump</td>
<td>50</td>
<td>150</td>
<td>7 8 9</td>
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<td>Epon</td>
<td>MVR-HP</td>
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<td>150</td>
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<td>150</td>
<td>7 8 9</td>
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<td>ecop</td>
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<td>1.2</td>
<td>130</td>
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<td>Mitsubishi Heavy Ind.</td>
<td>ETW-S</td>
<td>0.6</td>
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<td>Hybrid Energy</td>
<td>HyPAC-S</td>
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<td>120</td>
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<td>Johnson Controls</td>
<td>Cascade Heat Pump System</td>
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<td>7 8 9</td>
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<td>Fenagy</td>
<td>H1800-AW/WW</td>
<td>1.8</td>
<td>120</td>
<td>5 6</td>
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<td>Mayekawa HS Comp</td>
<td>HS-compressor</td>
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<td>120</td>
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<td>120</td>
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<td>120</td>
<td>9</td>
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<td>Fuji Electric</td>
<td>Steam Generation Heat Pump</td>
<td>0.03</td>
<td>120</td>
<td>9</td>
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<td>Emerson</td>
<td>Cascade Solution</td>
<td>0.03</td>
<td>120</td>
<td>9</td>
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<td>Skala Fabrikk</td>
<td>SkalUP</td>
<td>0.3</td>
<td>115</td>
<td>9</td>
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<td>Mayekawa EcoCircuit</td>
<td>Eco Circuit 100</td>
<td>0.1</td>
<td>100</td>
<td>8 9</td>
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</tbody>
</table>

Other suppliers:
- Ago Calora (150 °C)
- Ochsner (130 °C)
- Oillon (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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11 July 2023

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Commercial High-Temperature Heat Pumps for Supply Temperatures > 100 °C
Max. supply temperature vs. heating capacity of various HTHPs

Compressor type:
- Screw
- Piston
- Turbo
- Other

Refrigerant
- R718 (Water)
- R704 (Helium)
- R717 (Ammonia)
- HFOs (Hydrofluorolefine)
- R744 (CO₂)
- R601 (n-Pentane)
- R600 (n-Butane)
- R290 (Propane)

Based on data from IEA HPT Annex 58
https://heatpumpingtechnologies.org/annex58/task1
Commercial High-Temperature Heat Pumps for Supply Temperatures > 100 °C

Refrigerants in HTHPs

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

Natural 64%
HFO 18%
HFC 18%

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 1
## Commercial High-Temperature Heat Pumps for Supply Temperatures > 100 °C

### HTHP products for > 100 °C supply temperature

<table>
<thead>
<tr>
<th>HTHP supplier (High-Temperature Heat Pump)</th>
<th>Country</th>
<th>Product</th>
<th>Compressor type</th>
<th>Working fluid (Refrigerant)</th>
<th>Max. heating capacity (MW)</th>
<th>Max. supply temp. (°C)</th>
<th>TRL (Technology Readiness Level)</th>
<th>Spec. invest. cost (EUR/kWth)</th>
</tr>
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<tbody>
<tr>
<td>Spilling</td>
<td>DE</td>
<td>Steam Compressor</td>
<td>Piston (MVR)</td>
<td>R716 (water)</td>
<td>15</td>
<td>280</td>
<td>9</td>
<td>100 to 400</td>
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<td>Energin</td>
<td>NO</td>
<td>HighTemp</td>
<td>Piston</td>
<td>R704 (helium)</td>
<td>10</td>
<td>250</td>
<td>6</td>
<td>600 to 800</td>
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<tr>
<td>Qpinch</td>
<td>BE</td>
<td>Heat Transformer</td>
<td>Chemical heat transformer</td>
<td>R716, H2O, and derivatives</td>
<td>2</td>
<td>230</td>
<td>9</td>
<td>1000 to 2000</td>
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<tr>
<td>Piller</td>
<td>DE</td>
<td>VapoFan</td>
<td>Turbo (MVR)</td>
<td>R716</td>
<td>70</td>
<td>212</td>
<td>8 to 9</td>
<td>850</td>
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<tr>
<td>Olvondo</td>
<td>NO</td>
<td>HighLift</td>
<td>Piston (double acting)</td>
<td>R704</td>
<td>5</td>
<td>200</td>
<td>9</td>
<td>1200</td>
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<td>Turboden</td>
<td>NO</td>
<td>TC-C920</td>
<td>Turbo</td>
<td>R717 (ammonia), R718</td>
<td>30</td>
<td>200</td>
<td>7 to 9</td>
<td>300 to 700</td>
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<td>JP</td>
<td>HP</td>
<td>Rotary vane</td>
<td>R717</td>
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<td>180</td>
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<td>250 to 420</td>
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<td>Twin-screw (MVR)</td>
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<tr>
<td>Heaten</td>
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<td>HeatBooster</td>
<td>Reciprocating, custom design</td>
<td>HFOs (hydrofluorolefins)</td>
<td>6</td>
<td>165</td>
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<td>250 to 350</td>
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<td>DE</td>
<td>ThermoBooster</td>
<td>Piston</td>
<td>HFOs (hydrofluorolefins)</td>
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<td>165</td>
<td>6 to 8</td>
<td>150 to 1000</td>
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<tr>
<td>SRM</td>
<td>NO</td>
<td>compressor for water vapor</td>
<td>Screw (MVR)</td>
<td>R718</td>
<td>2</td>
<td>165</td>
<td>5</td>
<td>n.a.</td>
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<tr>
<td>Siemens Energy</td>
<td>DE</td>
<td>Industrial Heat Pump</td>
<td>Turbo (geared or single-shaft)</td>
<td>R1233zd(E), R1234ze(E)</td>
<td>0.7</td>
<td>160</td>
<td>9 (to 90 °C)</td>
<td>250 to 800</td>
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<td>Enertine</td>
<td>FR</td>
<td>HTHP</td>
<td>1- or 2-stage centrifugal</td>
<td>R1336mzz(Z), R1224yd(Z), R1233zd(E)</td>
<td>10</td>
<td>160</td>
<td>4 to 8</td>
<td>300 to 400</td>
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<tr>
<td>Well &amp; Sandvig</td>
<td>DK</td>
<td>WS Turbo Steam</td>
<td>Turbo (MVR)</td>
<td>R718</td>
<td>6</td>
<td>165</td>
<td>4 to 9</td>
<td>150 to 250</td>
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<td>ES</td>
<td>Rank® HP</td>
<td>Screw</td>
<td>R245fa, R1336mzz(Z), R1233zd(E)</td>
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<td>160</td>
<td>7</td>
<td>200 to 400</td>
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<td>MAN</td>
<td>DE</td>
<td>ETES CO2 Heat Pump</td>
<td>Centrifugal turbo with expander</td>
<td>R744 (CO2)</td>
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<td>150</td>
<td>7 to 8</td>
<td>300 to 500</td>
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<td>Epicon</td>
<td>NO</td>
<td>MVR-HP</td>
<td>Centrifugal fan / Blower</td>
<td>R718</td>
<td>30</td>
<td>150</td>
<td>9</td>
<td>200 to 400</td>
</tr>
<tr>
<td>Ohmia Industry</td>
<td>NO</td>
<td>SPP-H</td>
<td>Piston, Centrifugal fan (MVR)</td>
<td>R717, R718</td>
<td>10</td>
<td>150</td>
<td>7 to 8</td>
<td>n.a.</td>
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<td>escoria</td>
<td>AT</td>
<td>Rotation Heat Pump K7</td>
<td>Rotational heat pump</td>
<td>R744</td>
<td>0.75</td>
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<td>700</td>
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<td>FC-Compressor</td>
<td>Screw</td>
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<td>Piston/screw</td>
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<td>Johnson Controls</td>
<td>DK</td>
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<td>Reciprocating</td>
<td>R717, R600 (n-butane) (cascade)</td>
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<td>7 to 8</td>
<td>n.a.</td>
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<td>Feragyi</td>
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<td>DH600-AWWW</td>
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<td>R744</td>
<td>1.8</td>
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<td>Mayekawa HS Comp</td>
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<td>HS-compressor</td>
<td>Piston</td>
<td>R600 (n-butane)</td>
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<td>120</td>
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<td>450</td>
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<td>Reciprocating</td>
<td>R744 (CO2)</td>
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<td>120</td>
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<td>US</td>
<td>Cascade Solution</td>
<td>Scroll and EVI scroll</td>
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<td>n.a.</td>
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<td>Piston (semithermic)</td>
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<td>500 to 700</td>
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<td>Eco Circuit 100</td>
<td>Reciprocating</td>
<td>R1234ze(E)</td>
<td>0.1</td>
<td>100</td>
<td>8 to 9</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

**Note:**

- All information has been provided 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)
- ThermoDraFlt (120 °C)
- Combitherm (120 °C)
  - ...

**Large-scale:**

- Frietherm
- MAN Energy Solutions
- Turboden
- Mitsubishi MHPS
- Siemens Energy
  - ...

**Data source:**

IEA HPT Annex 58
[https://heatpumpingtechnologies.org/annex58/task1](https://heatpumpingtechnologies.org/annex58/task1)
Commercial High-Temperature Heat Pumps for Supply Temperatures > 100 °C

Operating maps of some industrial HTHPs
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


cordin.arpagaus@ost.ch
New Developments and Products for Supply Temperatures above 100 °C

Steam generating version of the ThermBooster™

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

[Image of steam generator with integrated condenser]
New Developments and Products for Supply Temperatures above 100 °C

Laboratory for testing the ThermBooster™

Image courtesy by SPH Sustainable Process Heat GmbH
New Developments and Products for Supply Temperatures above 100 °C

Applications of the ThermBooster™

<table>
<thead>
<tr>
<th>Application</th>
<th>Gelatine</th>
<th>Thermoplastic from waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat source</td>
<td>85/70 °C</td>
<td>75/65 °C (water)</td>
</tr>
<tr>
<td>Heat sink</td>
<td>812 kg/h steam at 2 bar</td>
<td>90/130 °C (hot water) for drying process</td>
</tr>
<tr>
<td>Heating capacity</td>
<td>514 kW</td>
<td>1’017 kW (2 cycles)</td>
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<tr>
<td>Cooling capacity</td>
<td>407 kW</td>
<td>809 kW</td>
</tr>
<tr>
<td>Electrical power</td>
<td>118 kW</td>
<td>229 kW (2 compressors)</td>
</tr>
<tr>
<td>COP</td>
<td>4.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Energy savings</td>
<td>4.1 GWhth/a</td>
<td>1.25 Mio. m³ gas/a</td>
</tr>
<tr>
<td>CO₂ emission reduction</td>
<td>550 t CO₂/a</td>
<td>~2’400 t CO₂/a</td>
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</tbody>
</table>

In cooperation with 2G® Energy AG

In cooperation with ubq

Image courtesy by SPH Sustainable Process Heat GmbH
New Developments and Products for Supply Temperatures above 100 °C

Heaten’s 1.5 MW\textsubscript{th} Very High-Temperature Heat Pump

- 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\textsubscript{th} soon” with piston compressors in V-shape

Image courtesy by Heaten AS
New Developments and Products for Supply Temperatures above 100 °C

Heaten’s HeatBooster Container Solutions

Images courtesy by Heaten AS
New Developments and Products for Supply Temperatures above 100 °C

HTHP Case Studies from

**IWWDS ER3b (1-stage with economizer)**
170 to 400 kW

- **Heat pump type**: IWWDS 120 ER3
- **Heating Capacity**: 158 kW
- **Application**: Local district heating network
- **Heat Sink**: 120 °C
- **Heat Source**: 45 to 55 °C
- **Source**: District heating network return line
- **Compressor**: Screw
- **Refrigerant**: ÖKO 1 (R245fa)
- **COP**: 2.0

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

**IWWDSS R2R3b (2-stage cascade)**
90 to 530 kW

- **Heat pump type**: IWWDS ER3b (1-stage with economizer)
- **Heating Capacity**: 170 to 400 kW
- **Application**: Hot water for production
- **Heat Sink**: 120 °C
- **Heat Source**: 55 °C
- **Source**: Water
- **Compressor**: Screw
- **Refrigerant**: R1233zd(E)
- **COP**: 2.47

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

Images courtesy by OCHSNER Energie Technik GmbH

<table>
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<tr>
<th>Mänttä-Vilpula (FIN)</th>
<th>Leather production Couro Azul (POR)</th>
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<td>Heat pump type</td>
<td>IWWDS 120 ER3</td>
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<tr>
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<tr>
<td>Application</td>
<td>Local district heating network</td>
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<tr>
<td>Heat Sink</td>
<td>120 °C</td>
</tr>
<tr>
<td>Heat Source</td>
<td>45 to 55 °C</td>
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<tr>
<td>Source</td>
<td>District heating network return line</td>
</tr>
<tr>
<td>Compressor</td>
<td>Screw</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>ÖKO 1 (R245fa)</td>
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<tr>
<td>COP</td>
<td>2.0</td>
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</table>

**Alternative Refrigerants:**
- R1233zd(E)
- R513 or R1234ze(E)
New Developments and Products for Supply Temperatures above 100 °C

Application Examples of HTHPs from CombiTherm

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
New Developments and Products for Supply Temperatures above 100 °C

HoegTemp Ultra High-Temperature heat pump from 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)
New Developments and Products for Supply Temperatures above 100 °C

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

Image courtesy by Enerin AS
New Developments and Products for Supply Temperatures above 100 °C

Rotation Heat Pump from ecop Technologies GmbH

- 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
- Variable temperature lift up to 55 K from sink outlet to source outlet

www.ecop.at

Image courtesy by ecop
New Developments and Products for Supply Temperatures above 100 °C

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- Variable temperature lift up to 55 K from sink outlet to source outlet
- www.ecop.at
New Developments and Products for Supply Temperatures above 100 °C

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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New Developments and Products for Supply Temperatures above 100 °C

Butane (R600) Heat Pump from Mayekawa Europe NV

- Heating capacity around 750 kW
- Reciprocating compressor
- 18 m² 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

<table>
<thead>
<tr>
<th>$T_{\text{source,in}}$ [°C]</th>
<th>$T_{\text{source,out}}$ [°C]</th>
<th>$T_{\text{sink,in}}$ [°C]</th>
<th>$T_{\text{sink,out}}$ [°C]</th>
<th>COP$_{\text{heating}}$ [-]</th>
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<tbody>
<tr>
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<td>65</td>
<td>70</td>
<td>120</td>
<td>4.8</td>
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<tr>
<td>72</td>
<td>60</td>
<td>70</td>
<td>120</td>
<td>4.4</td>
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<td>72</td>
<td>45</td>
<td>70</td>
<td>120</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Image courtesy by Mayekawa Europe NV

IHP Workshop ACEEE
11 July 2023

cordin.arpagaus@ost.ch
# New Developments and Products for Supply Temperatures above 100 °C

## Case studies & demo Sites ([www.push2heat.eu](http://www.push2heat.eu))

<table>
<thead>
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</thead>
<tbody>
<tr>
<td><strong>Plant owner</strong></td>
<td>Felix Schoeller Group</td>
<td>Cuartiere di Guarcino</td>
<td>Dynasol</td>
<td>QPinch facilities</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Weissenborn, Germany</td>
<td>Lazio, Italy</td>
<td>Santander, Spain</td>
<td>Antwerp, Belgium</td>
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<tr>
<td><strong>HP supplier</strong></td>
<td>SPH</td>
<td>Enertime</td>
<td>BS-Nova</td>
<td>QPinch</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>Piston compressor</td>
<td>Turbo compressor</td>
<td>Absorption Heat Transformer (H$_2$O/LiBr)</td>
<td>Thermochemical Heat Transformer</td>
</tr>
</tbody>
</table>

| **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 | 1.0 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 |
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

- **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 CO₂ 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., H₂O, CO₂, NH₃, helium, hydrocarbons) and synthetic HFOs with low GWP

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

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

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

DeCarbonisation of Cooling and Heating in Switzerland
www.sweet-decarb.ch

www.ost.ch/ies
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


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.


cordin.arpagaus@ost.ch
Backup Slides
Motivation: Process heat consumption & temperature levels

Europe EU-28 – Industrial sectors

<table>
<thead>
<tr>
<th>Heat Consumption (TWh/a)</th>
<th>EU-28</th>
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<tbody>
<tr>
<td>Space heating</td>
<td>297</td>
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<td>Hot water</td>
<td>25</td>
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<tr>
<td>PH &lt;60 °C</td>
<td>55</td>
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<tr>
<td>PH 60 to 80 °C</td>
<td>53</td>
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<tr>
<td>PH 80 to 100 °C</td>
<td>89</td>
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<tr>
<td>PH 100 to 150 °C</td>
<td>192</td>
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<tr>
<td>PH 150 to 200 °C</td>
<td>80</td>
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<tr>
<td>PH 200 to 500 °C</td>
<td>151</td>
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<tr>
<td>PH 500 to 1’000 °C</td>
<td>376</td>
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<tr>
<td>PH &gt;1’000 °C</td>
<td>504</td>
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<tr>
<td><strong>Total Heat Consumption (TWh/year)</strong></td>
<td>1’821</td>
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<tr>
<th>Process Heat Consumption (TWh/a)</th>
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<tbody>
<tr>
<td>Industrial sector</td>
<td>PH 100 to 150 °C</td>
<td>PH 150 to 200 °C</td>
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<td>Iron and steel</td>
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<td>7.3</td>
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<td>Chemical</td>
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<tr>
<td>Non-ferrous metal</td>
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<td>Non-metallic minerals</td>
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<td>Food and tobacco</td>
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<tr>
<td>Paper, pulp and print</td>
<td>10.0</td>
<td>39.4</td>
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<td>Machinery</td>
<td>6.9</td>
<td>2.9</td>
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<td>Wood and wood products</td>
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<td>Transport equipment</td>
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<tr>
<td>Textile and leather</td>
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<td>Other</td>
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<tr>
<td><strong>Total</strong></td>
<td>191</td>
<td>80</td>
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Potential HTHP Development Perspectives until 2030

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<th>Heating capacity</th>
<th>Supply temperature</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
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<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
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<tbody>
<tr>
<td>200 kW to 10 MW</td>
<td>160 °C</td>
<td>○</td>
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<tr>
<td>120 to 160 °C</td>
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<tr>
<td>&lt; 120 °C</td>
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<td>&gt; 120 °C</td>
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<td>&lt; 120 °C</td>
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</table>

- Prototypes available
- Full-scale demonstrators available
- Various HTHP technologies commercially available
- Established as preferred HTHP technology
- HTHP technologies commercially offered
- First demonstrations realized
- Prototype developments
- Technology advancements, upscaling
- Optimization of efficiency, costs, etc.
- Standardization, further improvements and novel applications
- Technology transfer to HTHP applications
- Testing and demonstration of prototypes
- Full-scale demonstration in industrial environment
- Commercial deployment of systems
- Integration studies with end-users

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

Headquarters of HTHP suppliers in Europe

<p>| | |</p>
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<td>1</td>
<td>Ecop (AT)</td>
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<td>Mayekawa MYCOM (BE)</td>
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<td>Weel and Sandvig (DK)</td>
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<td>Rank (ES)</td>
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<td>SRM (SE)</td>
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Japan

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<td>25</td>
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<td>KOBELCO (JP)</td>
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<td>Mitsubishi (JP)</td>
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</table>

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

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

Heat Source and Heat Sink Temperatures in °C

Natural Refrigerants

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Environmental aspects (F-gases, PFAS, TFA)

Formation of trifluoroacetic acid (TFA, CF$_3$COOH)

- 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
Environmental aspects (F-gases, PFAS, TFA)

Molar yield of TFA during atmospheric degradation of HFOs

- **Trifluoracetyl fluoride (TFF)**
  - Formula: CF$_3$-C(O)F
  - CAOrchard.arpagaus@ost.ch
  - $\text{CF}_3$-$\text{CF}=\text{CH}_2$
  - yield: $\approx 100\%$ (Guo et al., 2019)

- **Trifluoracetaldehyde**
  - Formula: CF$_3$-C(O)H
  - $\text{CF}_3$-$\text{CF}=\text{CH}=$
  - yield: $\approx <10\%$

- **Trifluoroacetic acid (TFA)**
  - Formula: CF$_3$-C(O)OH
  - $\text{CF}_3$-$\text{CF}=\text{CH}=$
  - yield: $\approx 97\%$ (Guo et al., 2019)
  - yield: $\approx <20\%$, because of $2 \times \text{CF}_3$-$\text{CH}=$ (Henne et al., 2012)
  - yield: $\approx 2\%$ (Sulbaek Andersen et al., 2018)
Efficiency (COP) of industrial heat pumps

\[ \text{COP}_H = 68.455 \cdot \Delta T_{\text{Lift}}^{-0.76} \]

Market Analysis – Diffusion of Innovation

Technology Adoption of Heat Pumps in Switzerland – Status 2022

- Innovators: 2.5%
- Early adopters: 13.5%
- Early majority: 34%
- Late majority: 34%
- Laggards: 16%

Market share of heat pumps in new heating installations: 65%

Buildings 2022 (CH)

Industry 2022 (CH)

IHP Workshop ACEEE 11 July 2023
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Market analysis

Market Barriers for Industrial Heat Pumps

Survey among 27 experts on heat pumps and heat recovery

- Energy Service Companies (ESCOs)
- Scientists
- Industry
- HP Manufacturers
- Planners/Consultants
- Others

Knowledge & Information

- Product acceptance: 22%
- Lack of suitable products: 7%
- Lack of knowledge of planners: 4%
- Lack of knowledge about available HPs: 19%
- High OPEX: 7%
- Obstructive electricity taxation: 4%
- Lack of Life Cycle Cost (LCC) analysis: 4%
- Expectation of short payback periods: 22%
- High CAPEX: 22%
- Fuel prices too low: 37%

Costs

- No suitable temperature levels: 11%
- Insufficient efficiency
- Unwanted change in production: 7%
- Preferred direct use of waste heat: 4%

## OPEX Parity COP and Temperature Lift

### Market Attractiveness

\[
COP = \frac{\text{Price}_{\text{Electricity}}}{\text{Price}_{\text{Gas}}} \cdot \eta_{\text{Gas Boiler}}
\]

\(\eta_{\text{Gas Boiler}} = 90\%\)

### Heat Pump vs. Gas Boiler (90% efficiency)

**OPEX Parity**

<table>
<thead>
<tr>
<th>Country</th>
<th>Gas Price</th>
<th>Electricity Price</th>
<th>Price Ratio</th>
<th>COP</th>
<th>(\Delta T_{\text{Lift}})</th>
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</table>

\[\Delta T_{\text{Lift}} = 68.455 \cdot (\text{Price Ratio}_{\text{Electricity}} / \text{Price Ratio}_{\text{Gas}})^{0.76}\]
The marked line shows the cost parity between the annual costs with a heat pump and a gas boiler.

Assumptions:
- **Heat pump**
  - Investment costs: 420 EUR/kW
  - Interest on capital: 5%
  - Useful life: 15 years
  - Annuity: 40.5 EUR/kW
  - Maintenance costs: 2.5% of 15 EUR/kW
- **Gas boiler**
  - Investment costs: 60 Euro/kW
  - Interest on capital: 5%
  - Useful life: 15 years
  - Annuity: 5.8 EUR/kW
  - Maintenance costs: 3% (Investment)
  - 2nd law efficiency ($\eta_{HP}$): 1) 45%
  - Gas boiler efficiency ($\eta_{Boiler}$): 80%
  - Operating hours: 2) 3'504 h/year
  - Gas price: 3) 0.0301 Euro/kWh

1) COP$_H$ = $\eta_{HP}$ \cdot $T_{\text{Sink,out}}$ / $\Delta T_{\text{Lift}}$; $T_{\text{Sink,out}}$ = 393.15 (120°C)
2) 40% x 365 days x 24 h = 3'504 h
3) Eurostat, EU-28, 2016


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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

Sensitivity Analysis

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<th>Parameter</th>
<th>Variation Factor</th>
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<td>Temperature price</td>
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<td>Cost factor planning &amp; integration</td>
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<tr>
<td>Efficiency of fuel boiler</td>
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<td>CO2 emissions factor of electricity</td>
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<td>Fuel price (gas, oil)</td>
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</table>

Reference Case (Ref)

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