Operation characteristics of heat pumps II

- calculation - bin method - example
- influence of operation conditions on HP effectivity
Example: family house

- **space heating**
  - heat loss 30 kW (-18 °C)
  - space heating demand **60 500 kWh/a**
  - climate defined by table, \( d = 235, \ t_{e,m} = 3,0 \) °C
  - heating system **50/40 °C**

- **hot water**
  - 6 persons, 60 l/per.day, heat losses 30 %
  - hot water temperature 55 °C, cold water temperature 10 °C
  - hot water heat demand = **8 950 kWh/a**
Example: heat demand
Example: heat pump

- ground source heat pump WPF 20
  - nominal heat output $Q_{HP} = 21.9 \text{ kW}$
  - $COP = 4.8$
Example

\[ Q_{\text{HP}} = 25.9 + 0.569 t_{v1} - 0.103 t_{k2} \]

- 35 °C
- 50 °C
- 60 °C
Example

$$COP = 8.6 + 0.091 \cdot t_{v1} - 0.104 \cdot t_{k2}$$
Example: boreholes

- ground source
  - input to evaporator dependent on ambient temperature

\[
t_{v1} = \max\left(0 \degree C; \min\left(0.15 \cdot t_e + 1.5 \degree C; 4.5 \degree C\right)\right)
\]
Example: heating system

- space heating regime (radiators)
  - nominal temperatures flow/return $t_{w1,N} = 50 \quad t_{w2,N} = 40 \, ^\circ\text{C}$
  - temperature exponent $n = 1,3$

$$t_{w1} = t_i + \frac{t_{w1,N} - t_{w2,N}}{2} \cdot \frac{t_i - t_e}{t_i - t_{e,N}} + \left(\frac{t_{w1,N} + t_{w2,N}}{2} - t_i\right) \cdot \left(\frac{t_i - t_e}{t_i - t_{e,N}}\right)^{1/n}$$

$$t_{k2} = t_{w1} + 3 \, \text{K}$$

weather compensation curve
Example: hot water

- **hot water regime**
  - requirement $t_{HW} = 55 \, ^\circ C$

\[ t_{k2} = t_{HW} + 5 \, K \]
Example: heat demand
Prague: temperature histogram

<table>
<thead>
<tr>
<th>te,lim,d,j</th>
<th>te,lim,h,j</th>
<th>te,m,j</th>
<th>tj</th>
<th>tkum,j</th>
<th>DH20/13</th>
<th>DH20/13,kum</th>
<th>fSH</th>
<th>fHW</th>
</tr>
</thead>
<tbody>
<tr>
<td>-18</td>
<td>-17</td>
<td>-17,5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0,000</td>
<td>0,000</td>
</tr>
<tr>
<td>-17</td>
<td>-16</td>
<td>-16,5</td>
<td>5</td>
<td>5</td>
<td>183</td>
<td>183</td>
<td>0,002</td>
<td>0,001</td>
</tr>
<tr>
<td>-16</td>
<td>-15</td>
<td>-15,5</td>
<td>5</td>
<td>10</td>
<td>178</td>
<td>360</td>
<td>0,002</td>
<td>0,001</td>
</tr>
<tr>
<td><strong>-15</strong></td>
<td><strong>-14</strong></td>
<td><strong>-14,5</strong></td>
<td><strong>14</strong></td>
<td>24</td>
<td>483</td>
<td><strong>843</strong></td>
<td><strong>0,005</strong></td>
<td><strong>0,002</strong></td>
</tr>
<tr>
<td>-14</td>
<td>-13</td>
<td>-13,5</td>
<td>14</td>
<td>38</td>
<td>469</td>
<td>1312</td>
<td>0,005</td>
<td>0,002</td>
</tr>
</tbody>
</table>

| 8 | 9 | 8,5 | 334 | 4496 | 3841 | 82225 | 0,040 | 0,038 |
| 9 | 10 | 9,5 | 387 | 4883 | 4064 | 86289 | 0,042 | 0,044 |
| 10 | 11 | 10,5 | 341 | 5224 | 3240 | 89528 | 0,034 | 0,039 |
| 11 | 12 | 11,5 | 408 | 5632 | 3468 | 92996 | 0,036 | 0,047 |
| 12 | 13 | 12,5 | 376 | 6008 | 2820 | 95816 | 0,029 | 0,043 |
| 13 | 14 | 13,5 | 322 | 6330 |     |       |       |      |
| 14 | 15 | 14,5 | 326 | 6656 |     |       |       |      |
| 15 | 16 | 15,5 | 320 | 6976 |     |       |       |      |
| 16 | 17 | 16,5 | 273 | 7249 |     |       |       |      |
| 27 | 28 | 27,5 | 38 | 8720 |     |       |       |      |
| 28 | 29 | 28,5 | 30 | 8750 |     |       |       |      |
| 29 | 30 | 29,5 | 6  | 8756 |     |       |       |      |
| 30 | 31 | 30,5 | 4  | 8760 |     |       |       |      |
| 31 | 32 | 31,5 | 0  | 8760 |     |       |       |      |

| 8760 |     |     |     |     |     | 3992 | 1,000 | 1,000 |
Example calculation

<table>
<thead>
<tr>
<th>$t_{em,j} = -14.5 \degree C$</th>
<th>$t_{em,j} = 2.5 \degree C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_j = 14 , h$</td>
<td>$\tau_j = 433 , h$</td>
</tr>
<tr>
<td>$f_{HW} = 0.0016 \approx 0.002 \text{ in table}$</td>
<td>$f_{HW} = 0.049$</td>
</tr>
<tr>
<td>$f_{SH} = 0.005 \text{ in table}$</td>
<td>$f_{SH} = 0.079$</td>
</tr>
<tr>
<td>$Q_{HW} = 14 , kWh$</td>
<td>$Q_{HW} = 442 , kWh$</td>
</tr>
<tr>
<td>$Q_{SH} = 305 , kWh$</td>
<td>$Q_{SH} = 4785 , kWh$</td>
</tr>
</tbody>
</table>
Example calculation

\[ t_{v1} = \max(0 \, ^\circ\text{C}; \min(0.15 \cdot t_e + 1.5 \, ^\circ\text{C}; 4.5 \, ^\circ\text{C})) \]

\[ t_{k2,\text{HW}} = t_{k2} = t_{HW} + 5 \, \text{K} \quad \text{requirement } t_{HW} = 55 \, ^\circ\text{C} \]

\[ t_{k2,\text{SH}} = t_{k2} = t_{w1} + 3 \, \text{K} \]

\[
t_w = \left( t_i + \frac{t_{w1,N} - t_{w2,N}}{2} \cdot \frac{t_i - t_e}{t_i - t_{e,N}} + \left( \frac{t_{w1,N} + t_{w2,N}}{2} \right) - t_i \right) \cdot \left( \frac{t_i - t_e}{t_i - t_{e,N}} \right)^{1/n}
\]

\[ Q_{\text{HP,HW}} = Q_{\text{HP}} = f(t_{v1}, t_{k2}), \quad Q_{\text{HP}} = 25.9 + 0.569 \cdot t_{v1} - 0.103 \cdot t_{k2} \]

\[ \text{COP}_{\text{HW}} = \text{COP} = f(t_{v1}, t_{k2}) \quad \text{COP} = 8.6 + 0.091 \cdot t_{v1} - 0.104 \cdot t_{k2} \]

\[ Q_{\text{HP,SH}} = \]

\[ \text{COP}_{\text{SH}} = \]
### Example calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{v1}$</td>
<td>0,0 °C</td>
<td>$t_{v1}$</td>
<td>1,9 °C</td>
</tr>
<tr>
<td>$t_{k2,HW}$</td>
<td>60,0 °C</td>
<td>$t_{k2,HW}$</td>
<td>60,0 °C</td>
</tr>
<tr>
<td>$t_{k2,SH}$</td>
<td>50,7 °C</td>
<td>$t_{k2,SH}$</td>
<td>39,1 °C</td>
</tr>
<tr>
<td>$Q_{HP,HW}$</td>
<td>19,7 kW</td>
<td>$Q_{HP,HW}$</td>
<td>20,8 kW</td>
</tr>
<tr>
<td>$COP_{HW}$</td>
<td>2,4</td>
<td>$COP_{HW}$</td>
<td>2,5</td>
</tr>
<tr>
<td>$Q_{HP,SH}$</td>
<td>20,7 kW</td>
<td>$Q_{HP,SH}$</td>
<td>22,9 kW</td>
</tr>
<tr>
<td>$COP_{SH}$</td>
<td>3,3</td>
<td>$COP_{SH}$</td>
<td>4,7</td>
</tr>
</tbody>
</table>
Example calculation

\[
Q_{\text{HP,HW,avail}} = Q_{\text{HP,available,j}} = \dot{Q}_{\text{HP,j}} \cdot \tau_j
\]

\[
Q_{\text{HP,HW,del}} = Q_{\text{HP,delivered,j}} = \min(Q_{\text{HP,available,j}}, Q_{\text{HW,j}})
\]

\[
E_{\text{HP,HW}} = E_{\text{HP,j}} = \frac{Q_{\text{HP,delivered,j}}}{COP_j}
\]

\[
\tau_{\text{HP,HW}} = \tau_{\text{HP,j}} = \frac{Q_{\text{HP,delivered,j}}}{\dot{Q}_{\text{HP,j}}}
\]

\[
Q_{\text{bu,HW}} = Q_{\text{bu,HW}} = Q_{\text{HW,j}} - Q_{\text{HP,delivered,j}}
\]
### Example calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{HP,HW,avail}$</td>
<td>276 kWh</td>
<td>$Q_{HP,HW,avail}$</td>
<td>9001 kWh</td>
</tr>
<tr>
<td>$Q_{HP,HW,del}$</td>
<td>14 kWh</td>
<td>$Q_{HP,HW,del}$</td>
<td>442 kWh</td>
</tr>
<tr>
<td>$E_{HP,HW}$</td>
<td>6 kWh</td>
<td>$E_{HP,HW}$</td>
<td>175 kWh</td>
</tr>
<tr>
<td>$\tau_{HP,HW}$</td>
<td>0.7 h</td>
<td>$\tau_{HP,HW}$</td>
<td>21.3 h</td>
</tr>
<tr>
<td>$Q_{bu,HW}$</td>
<td>0 kWh</td>
<td>$Q_{bu,HW}$</td>
<td>0 kWh</td>
</tr>
</tbody>
</table>
Example calculation

\[ \tau_{HP,SH,\text{avail}} = 13,3 \text{ h} \]
\[ Q_{HP,SH,\text{avail}} = 274 \text{ kWh} \]
\[ Q_{HP,SH,\text{del}} = 274 \text{ kWh} \]
\[ E_{HP,SH} = 83 \text{ kWh} \]
\[ \tau_{HP,SH} = 13,3 \text{ h} \]
\[ Q_{bu,SH} = 31 \text{ kWh} \]

\[ \tau_{HP,SH,\text{avail}} = 411,7 \text{ h} \]
\[ Q_{HP,SH,\text{avail}} = 9446 \text{ kWh} \]
\[ Q_{HP,SH,\text{del}} = 4785 \text{ kWh} \]
\[ E_{HP,SH} = 1016 \text{ kWh} \]
\[ \tau_{HP,SH} = 208,5 \text{ h} \]
\[ Q_{bu,SH} = 0 \text{ kWh} \]
Bin method: annual results

total delivered energy by heat pump

\[ Q_{HP,\text{delivered}} = \sum_{j} Q_{HP,\text{delivered},j} \]

total delivered energy by back up heater

\[ Q_{bu} = \sum_{j} Q_{bu,j} \]

total electricity for heat pump

\[ E_{HP} = \sum_{j} E_{HP,j} \]

total electricity for back up heater

\[ E_{bu} = \sum_{j} E_{bu,j} \]

total electricity for auxiliaries

\[ E_{aux} = \sum_{j} E_{aux,j} \]

seasonal performance factor

\[ SPF = \frac{Q_{HP,\text{delivered}} + Q_{bu}}{E_{HP} + E_{bu} + E_{aux}} \]
Annual results

$\text{SPF}_{\text{HW}} = 2.60$

$\text{SPF}_{\text{SH}} = 4.61$

$\text{SPF} = 4.17$
Standard house

Passive house
Standard house

- **space heating**
  - 160 m²
  - heat loss 10 kW (-12 °C)
  - SH heat demand 21 500 kWh/a (135 kWh/m².a),
  - typical meteorological year in Prague
  - heating system 50/40 °C 35/30 °C

- **hot water**
  - 4 persons, 45 l/per.day, heat losses 15 %
  - hot water temperature 55 °C, cold water temperature 15 °C
  - hot water heat demand 3 500 kWh/a (14 % from total demand)
Standard house

![Energy Consumption Chart]

- **kWh**
- **hot water**
- **heating**

Months:
- leden
- únor
- březen
- duben
- květen
- červen
- červenec
- srpen
- září
- říjen
- listopad
- prosinec

Energy consumption for different months.
Heat pump air-water

heat output 8.1 kW and COP = 3.4 … at A2/W35

<table>
<thead>
<tr>
<th>SPF</th>
<th>SPF&lt;sub&gt;HW&lt;/sub&gt;</th>
<th>SPF&lt;sub&gt;VSH&lt;/sub&gt;</th>
<th>SPF&lt;sub&gt;sys&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.50</td>
<td>2.84</td>
<td>2.79</td>
</tr>
<tr>
<td>50/40</td>
<td>35/30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.50</td>
<td>2.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.31</td>
<td>3.17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Heat pump ground-water

heat output 9.9 kW and $COP = 4.5 \ldots$ at $B0/W35

\[\text{SPF}_{\text{HW}} = 2.30 \quad \text{and} \quad 35/30\]
\[\text{SPF}_{\text{SH}} = 3.61 \quad \text{and} \quad 4.62\]
\[\text{SPF}_{\text{sys}} = 3.35 \quad \text{and} \quad 4.05\]
Standard house

- recommendations for SPF from EN 15 450 can be met
  - high space heating demand compared to hot water preparation
  - low temperature heating system
  - high coverage of heat demand by heat pump (requirement for monovalent solutions)
  - well designed low-potential heat source
  - usual concept of heat pumps
Passive house

- **space heating**
  - 160 m²
  - heat loss 2.7 kW (-12 °C)
  - SH heat demand 3 200 kWh/a (20 kWh/m².a),
  - typical meteorological year in Prague
  - heating system 35/30 °C

- **hot water**
  - 4 persons, 45 l/per.day, heat losses 15 %
  - hot water temperature 55 °C, cold water temperature 15 °C
  - hot water heat demand 3 500 kWh/a (52 % from total demand)
Passive house

- **hot water**
- **heating**

Months: leden, únor, březen, duben, květen, červen, červenc, srpen, září, říjen, listopad, prosinec

kWh: 0-1400
Heat pump air-water

heat output 6.7 kW and COP = 3.2 … at A2/W35

SPF_{SH} = 2.94

SPF_{HW} = 2.40

SPF = 2.63
Heat pump ground-water

heat output 5,8 kW and COP = 4,3 … at B0/W35

SPF_{SH} = 4,15
SPF_{HW} = 2,12
SPF = 2,76
Passive house

- recommendation for SPF from EN 15450 cannot be met despite
  - low temperature system
  - monovalent solution
  - well designed low potential heat source
  but at
  - usual concept of heat pump
  - high hot water heat demand when compared to space heating (high temperature)

- gas boiler + solar system = 20 to 30 % lower primary energy consumption
Quo vadis heat pump in passive?

- reduction of hot water temperature to 45 °C
  - restriction of thermal comfort
  - hygienic requirements

- concept of heat pump for more effective water heating
  - heat pumps with subcooler to preheat cold water
  - cascade water heating, two stores in series, stratified heating