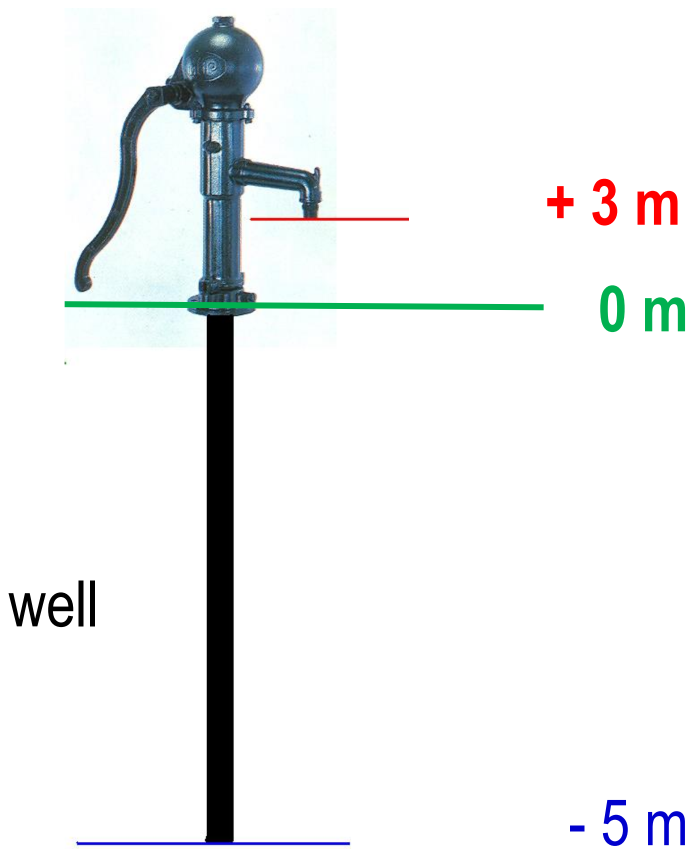
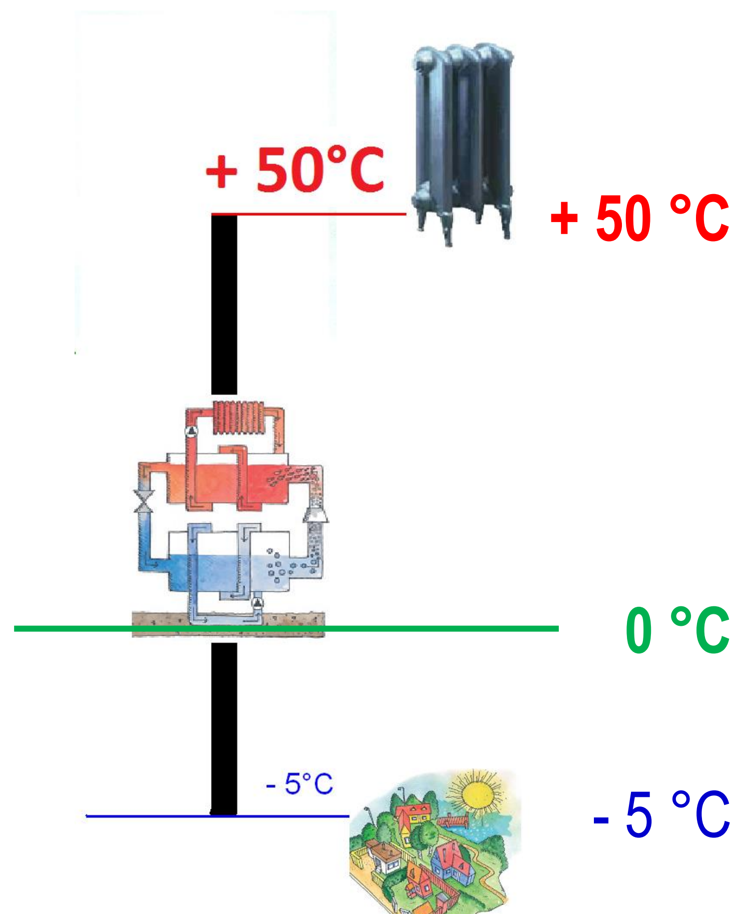
Operation characteristics of heat pumps

- seasonal performance factor
- **calculation - bin method**
- influence of operation conditions on HP effectivity

WATER PUMP X HEAT PUMP

Water **flow** =	**Quantity**	= Heat „**flow**“
Height =	**Quality**	= Temperature „**height**“





Declared *COP* of heat pump

- producer has tested the heat pump for given conditions

brine-water	B0/W35	$COP = 4.3$
water-water	W10/W35	$COP = 5.1$
air-water	A2/W35	$COP = 3.1$

- is it a **REAL** coefficient of performance?
- how about climate conditions?
- how about different operation conditions?
- **how to calculate total annual electricity consumption?**

Operation

- declared COP x real COP
- COP is changing with operation conditions
  - variable temperature of heat source (air, surface water)
  - constant temperature of heat source (water well, ground)
  - variable heating water temperature (equithermal control)
  - hot water preparation – **heating to 55 °C**, significant decrease of performance

How to calculate seasonal performance factor?

Minimum annual COP

- **to effective replacement of the primary fuel (fossil fuels)**
- **heat generator:** transformation of primary fuel

with efficiency η_{hg} (e.g. gas boiler)

$$Q_{p1} = \frac{Q_{del}}{\eta_{hg}}$$

Q_{p1} … primary fuel energy

Q_{del} … delivered heat energy

η_{hg} … heat generator efficiency

- **heat pump:** transformation of primary fuel to electricity with efficiency η_e and transformation of electricity to heat from heat pump (use of **ambient renewable** energy) with annual ***COP*** of the heat pump

$$Q_{p2} = \frac{E_{HP}}{\eta_e} = \frac{Q_{del}}{COP} \cdot \frac{1}{\eta_e}$$

E_{HP} … el.energy consumption HP

η_e … primary fuel transformation efficiency

Q_{del} … delivered heat energy

COP … annual COP of HP

Minimum annual COP

- minimum annual *COP* of heat pump to replace primary fuel (including heat store)

$$Q_{p2} < Q_{p1} \qquad\qquad COP > \frac{\eta_{hg}}{\eta_e}$$

- **gas boiler** η_{hg} = 0.76 (operation efficiency, not nominal),

  power plant efficiency (0.35) + network losses … η_e = 0.30

  minimum ***COP* > 2.5**

- **gas condensing boiler** η_{hg} = 0.93, electricity production efficiency η_e = 0.30

  minimum ***COP* > 3.1**

- **can we reach this COP?**
- **do heat pumps save primary energy? are heat pumps renewables?**

  isn't better to generate the heat from fossil fuels directly?

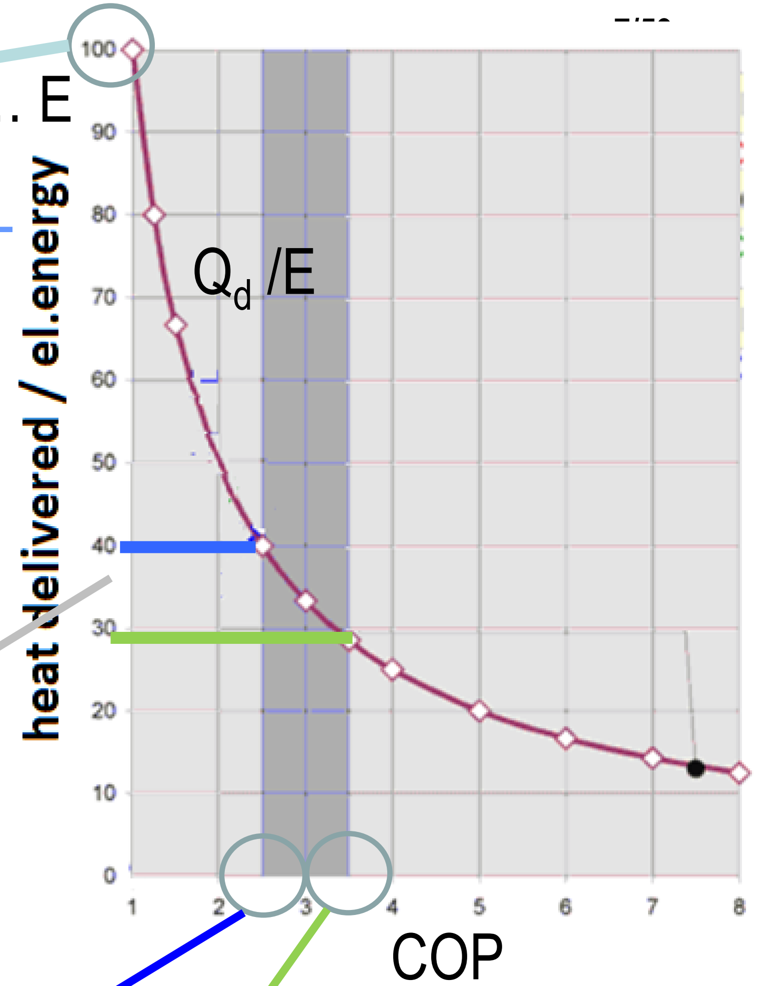
Optimum *COP*?

Electro-boiler
has „COP“=1… E

- **energy savings are not proportional to *COP* !**

$$Q_{sav} = Q_d - E = Q_d - \frac{Q_d}{COP} = Q_d\left(1 - \frac{1}{COP}\right)$$

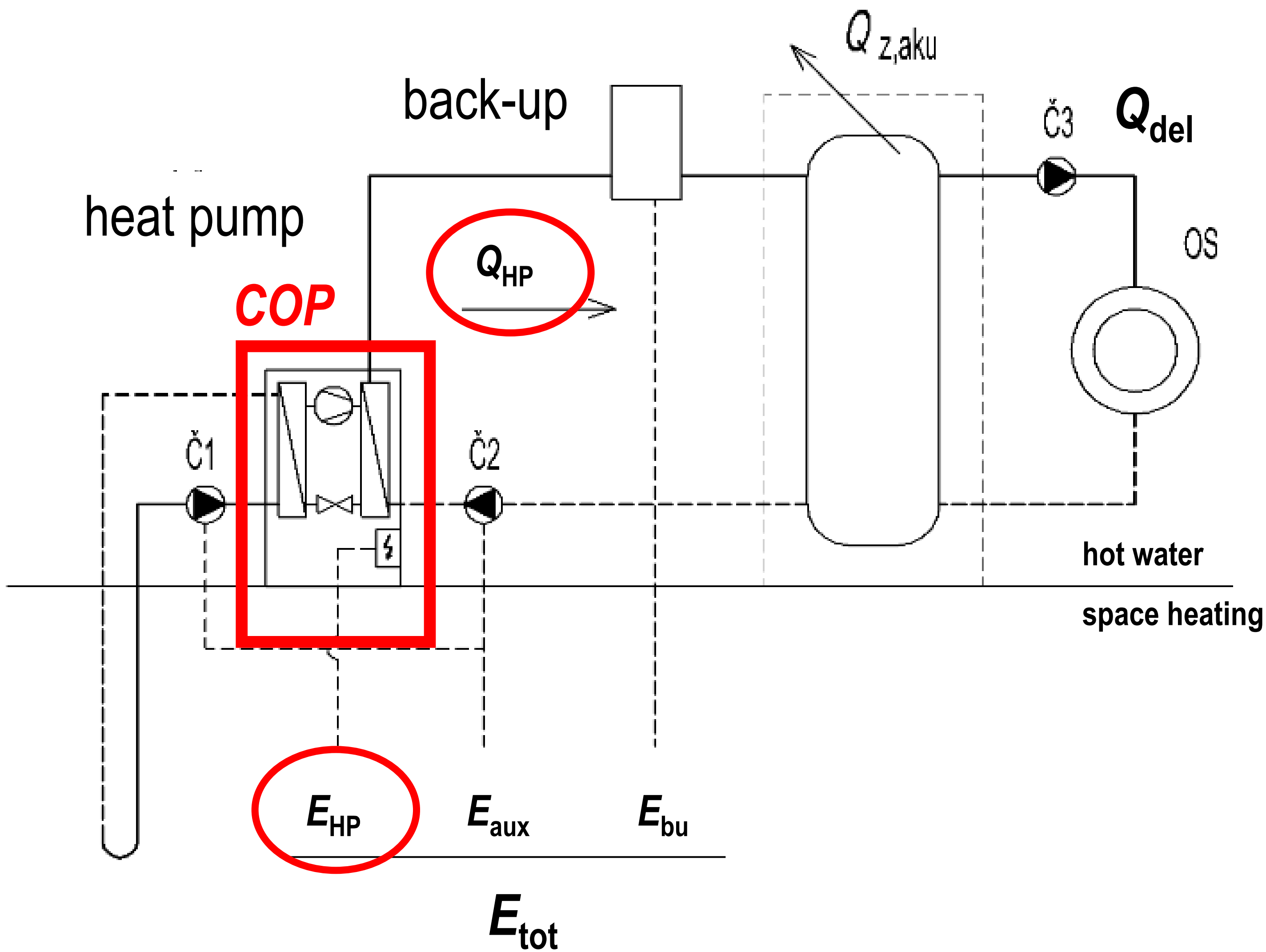
- analogy with heat insulation
- **double *COP*** ≠ double savings,
- double COP = only **25%** savings



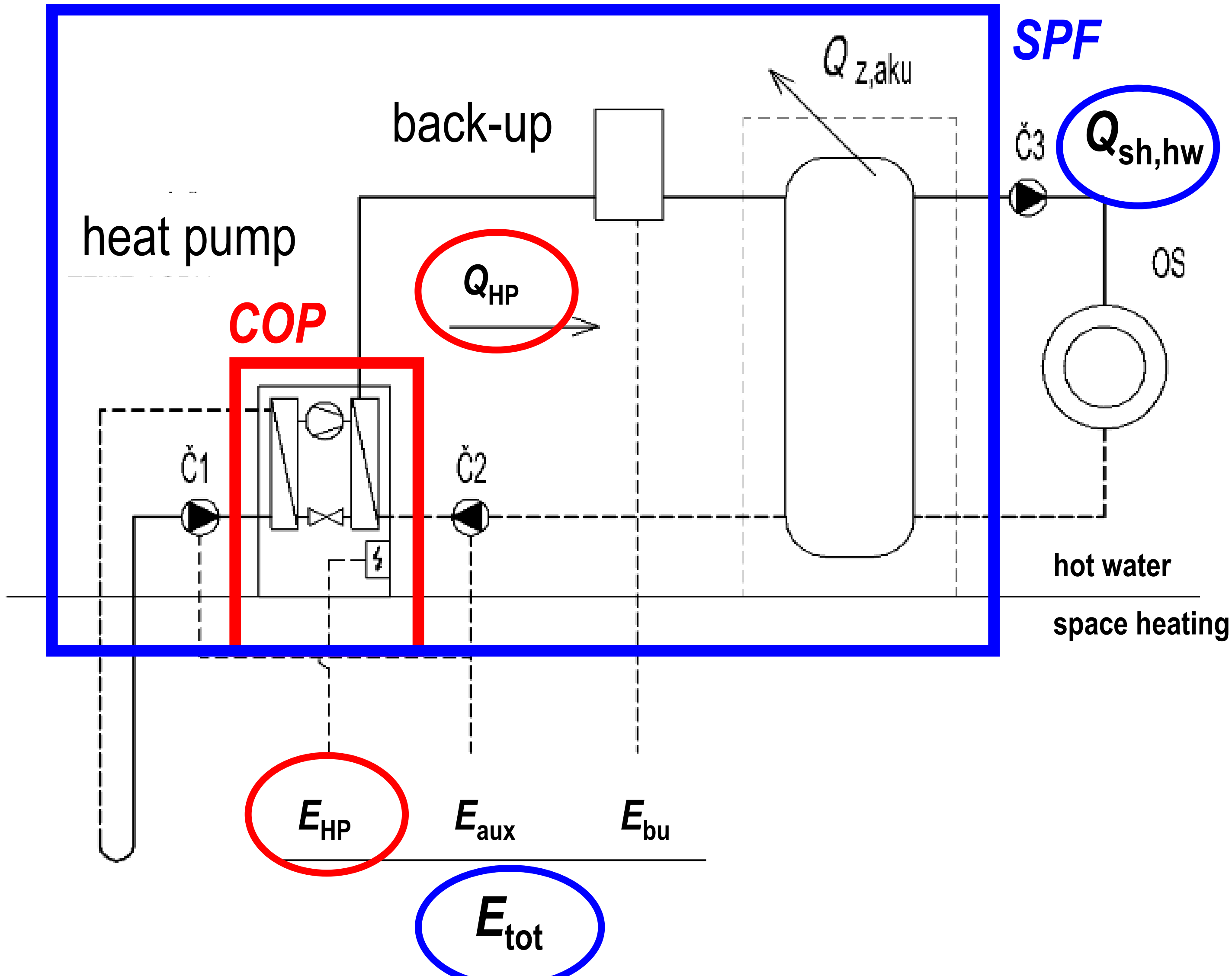
EXAMPLE:
difference in savings between heat pump with *COP* = **2,5** and **3,5** is not so large : - 11% (29% to 40%)
important is **quality heat pump** (longlife)

Seasonal performance factor of HP

$$COP = \frac{Q_{HP}}{E_{HP}}$$



Seasonal performance factor of system



$$COP = \frac{Q_{HP}}{E_{HP}}$$

$$SPF = \frac{Q_{sh,hw}}{E_{tot}}$$

Annual balance of heat pump

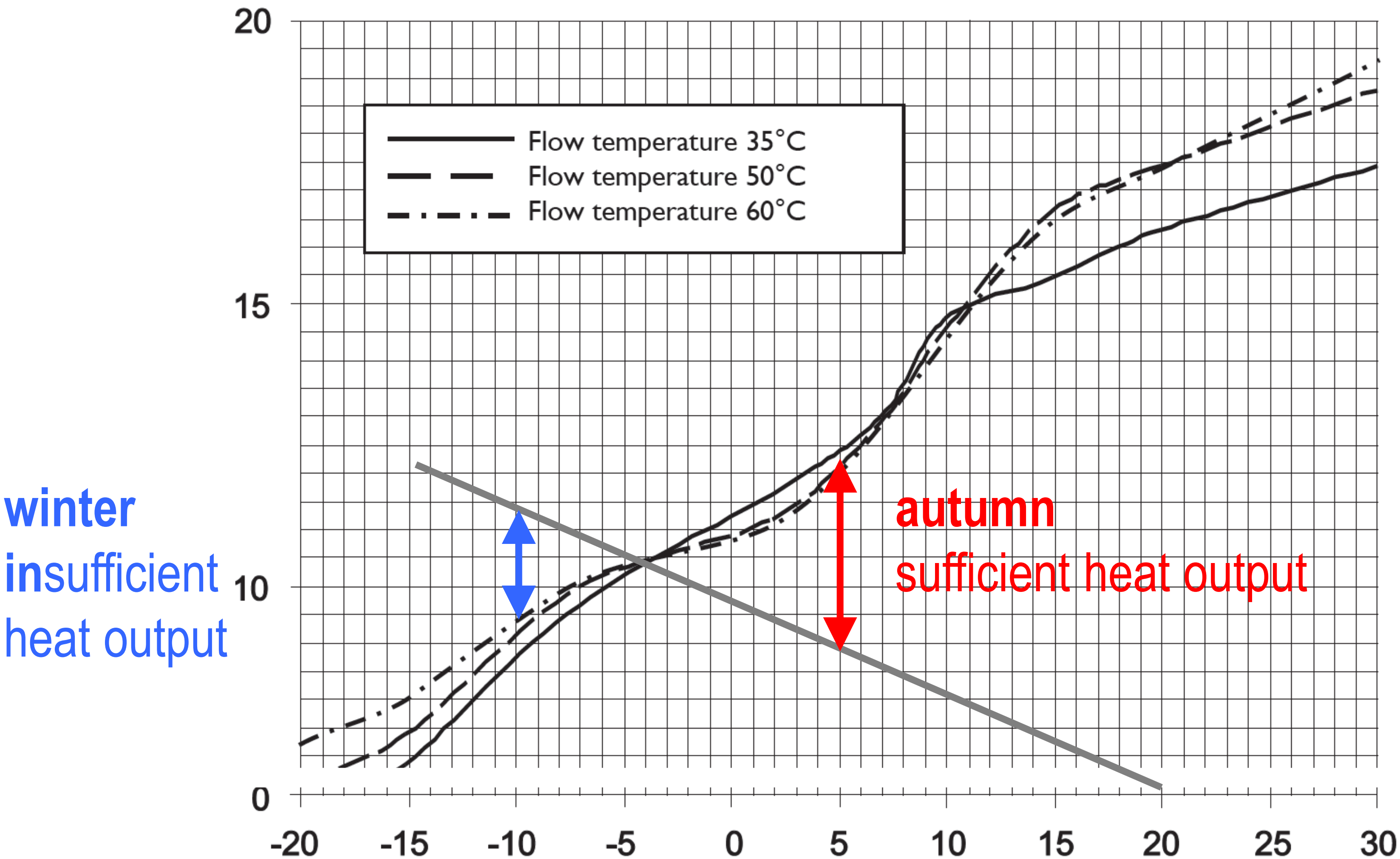
Annual balance of heat pump

- **target**
  - real electricity consumption of heat pump
  - real electricity consumption of back-up heater
  - evaluation of *SPF*
  - evaluation of primary energy needs, CO_2 emission savings

- **simple calculation method**
  - simple calculation with Excel
  - climatic parameters (temperature frequency histogram for given location)

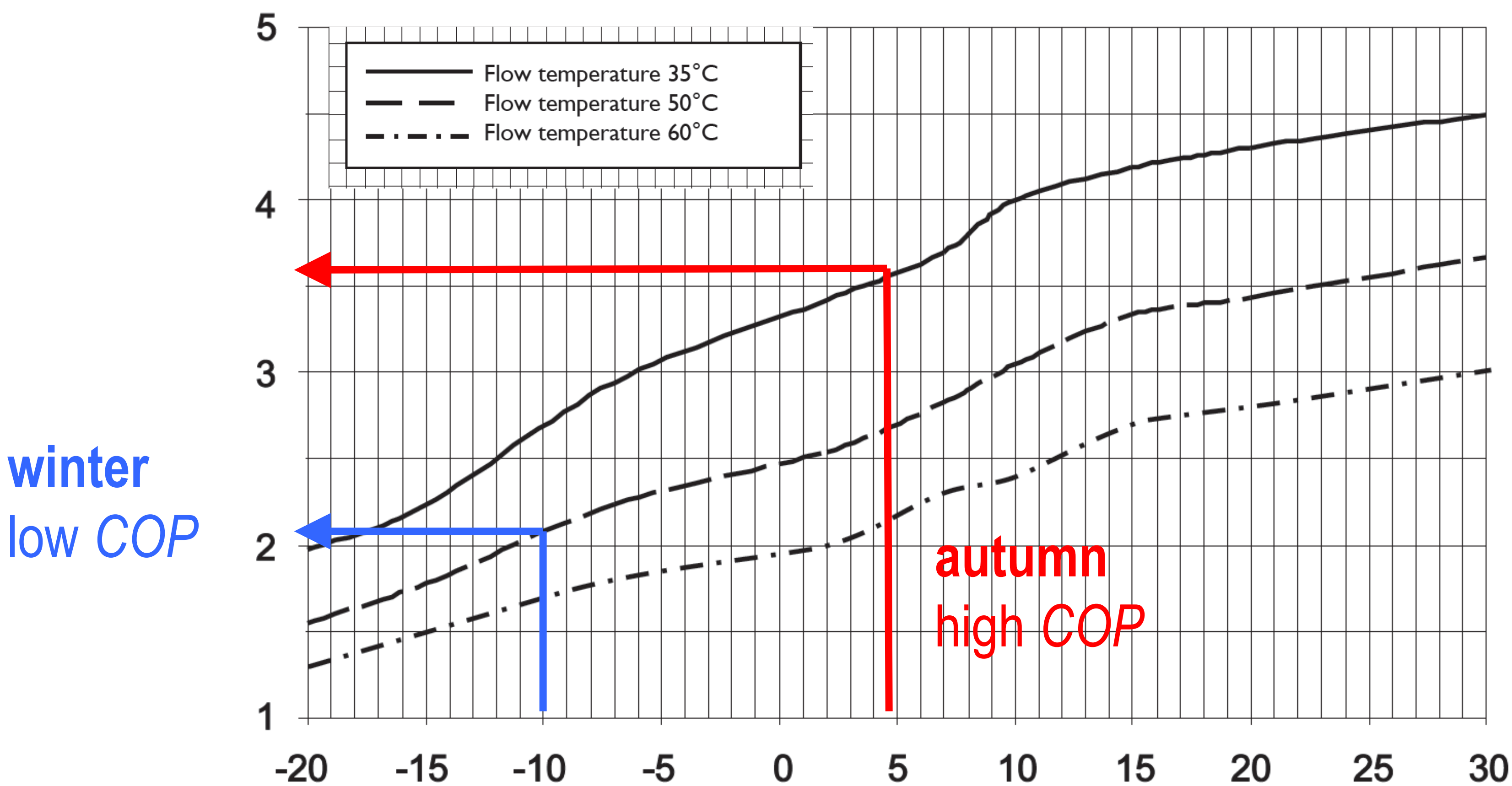
Why detailed balance?

unstable power output during the year!



Why detailed balance?

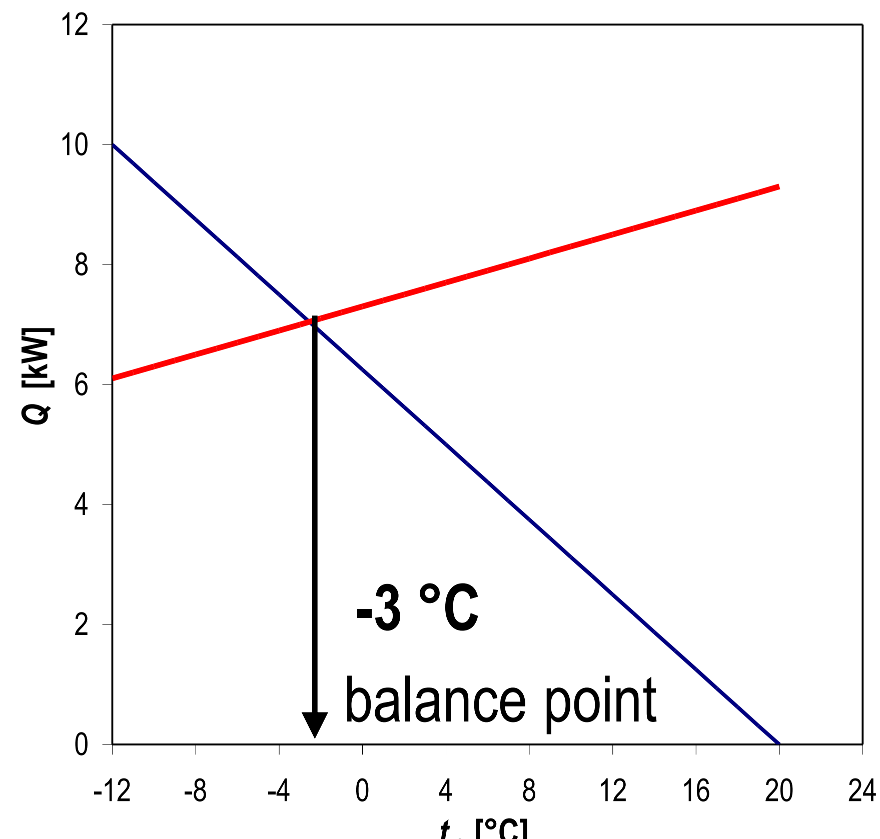
unstable *COP* during year



Energy balance for heat pump

- **monthly method is not possible (!)**
  - average monthly temperatures are exceptionally under balance point

	Prague	Budweis	Hradec	Brno
I	**-1,5**	**-2**	**-2,1**	**-2**
II	0	-0,9	-1	-0,6
III	3,2	3	2,7	3,7
IV	8,8	7,4	7,4	8,7
V	13,6	12,7	12,8	14,1
VI	17,3	15,7	15,6	16,9
VII	19,2	17,5	17,4	18,8
VIII	18,6	16,6	16,8	17,8
IX	14,9	12,9	13,5	14
X	9,4	7,7	8,3	8,7
XI	3,2	2,8	3,1	3,6
XII	-0,2	-0,4	-0,4	-0,2



Energy balance for heat pump

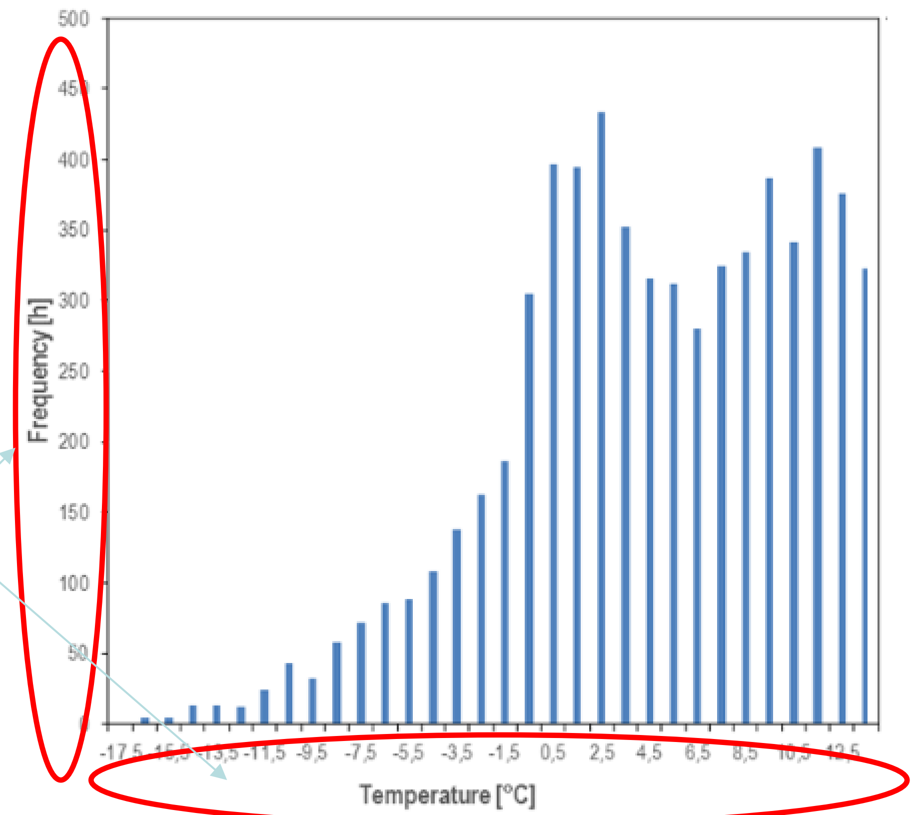
bin method

Energy balance for heat pump

- **bin method,** method of temperature bins (intervals)
- The "**bin method**" refers to a procedure where yearly (seasonal) weather data is sorted into discrete groups (**bins**) of weather conditions. Each **bin** contains the number of average hours of occurrence during a year of a particular range of weather condition.

Energy balance for heat pump

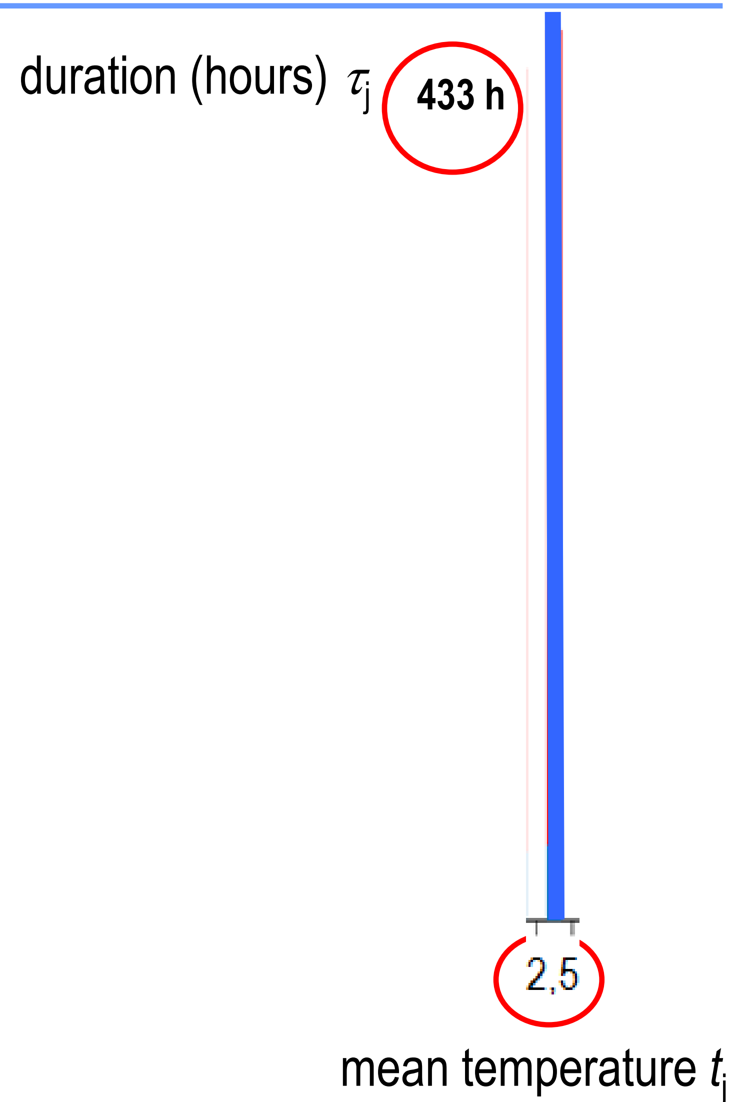
- **bin method, method of temperature bins (intervals)**
  - standardized method in EN 15316-4-2
  - using the temperature histogram for heating season or whole year
  - resolution of bins 1 K
  - each **temperature bin** is characterized by:
    - mean temperature t_j
    - duration (hours) τ_j



Energy balance for heat pump

Example: **temperature bin +2,5°C**

in Prague condition



(from +2°C to +3°C)

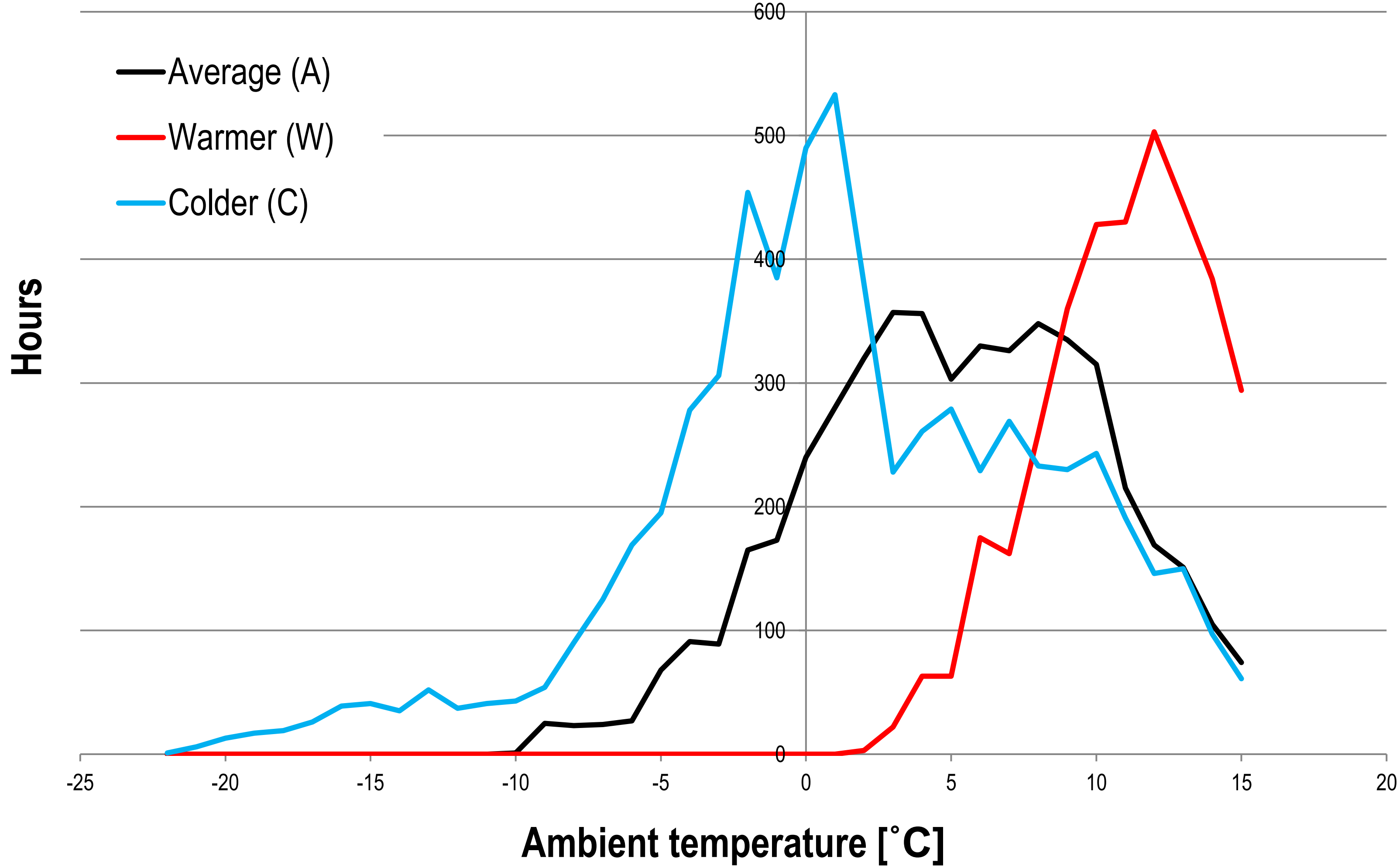
Climatic data

***Average* – Strasbourg (-10 °C)**

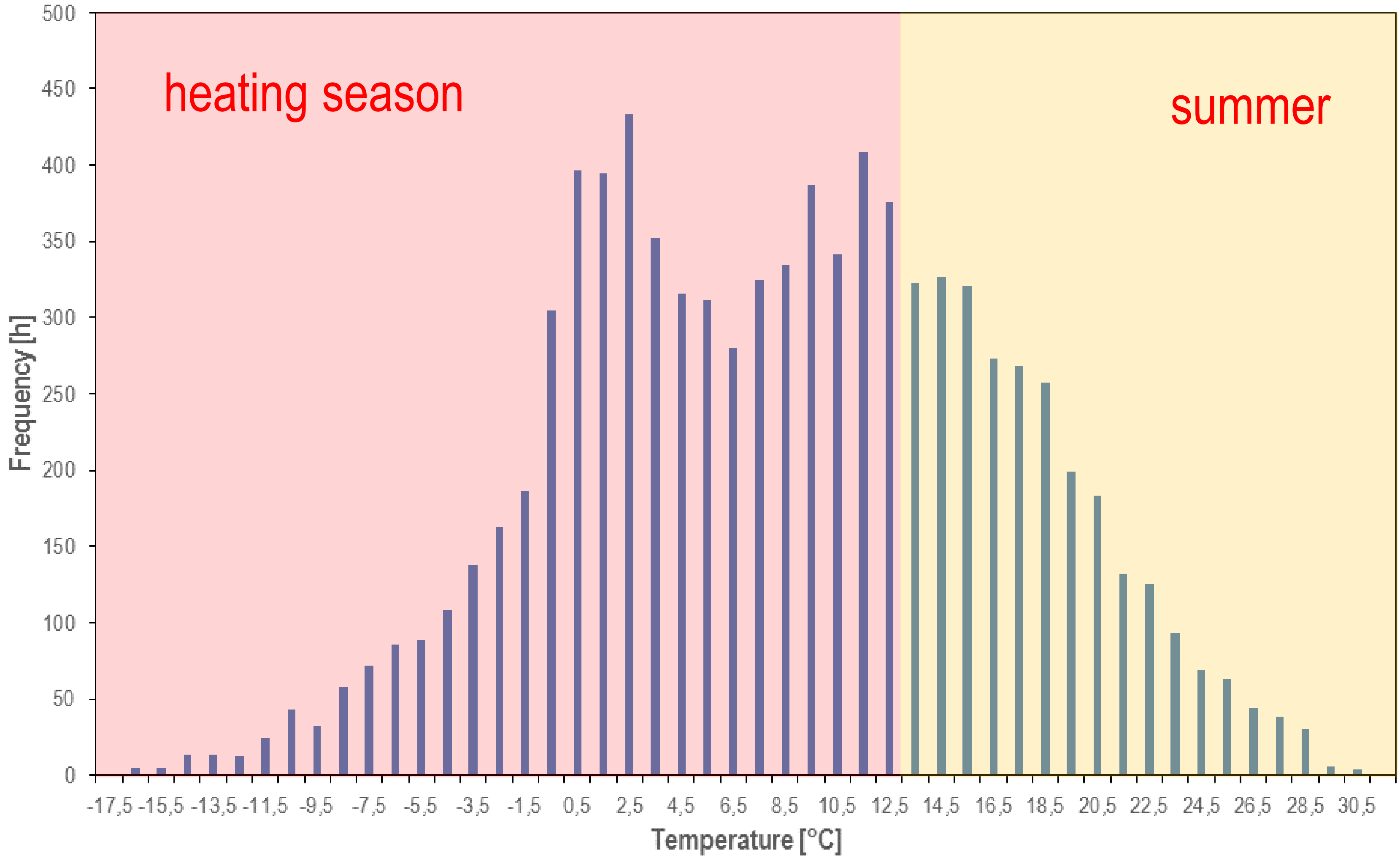
Warmer – Athens (+2 °C)

Colder – Helsinki (-22 °C)

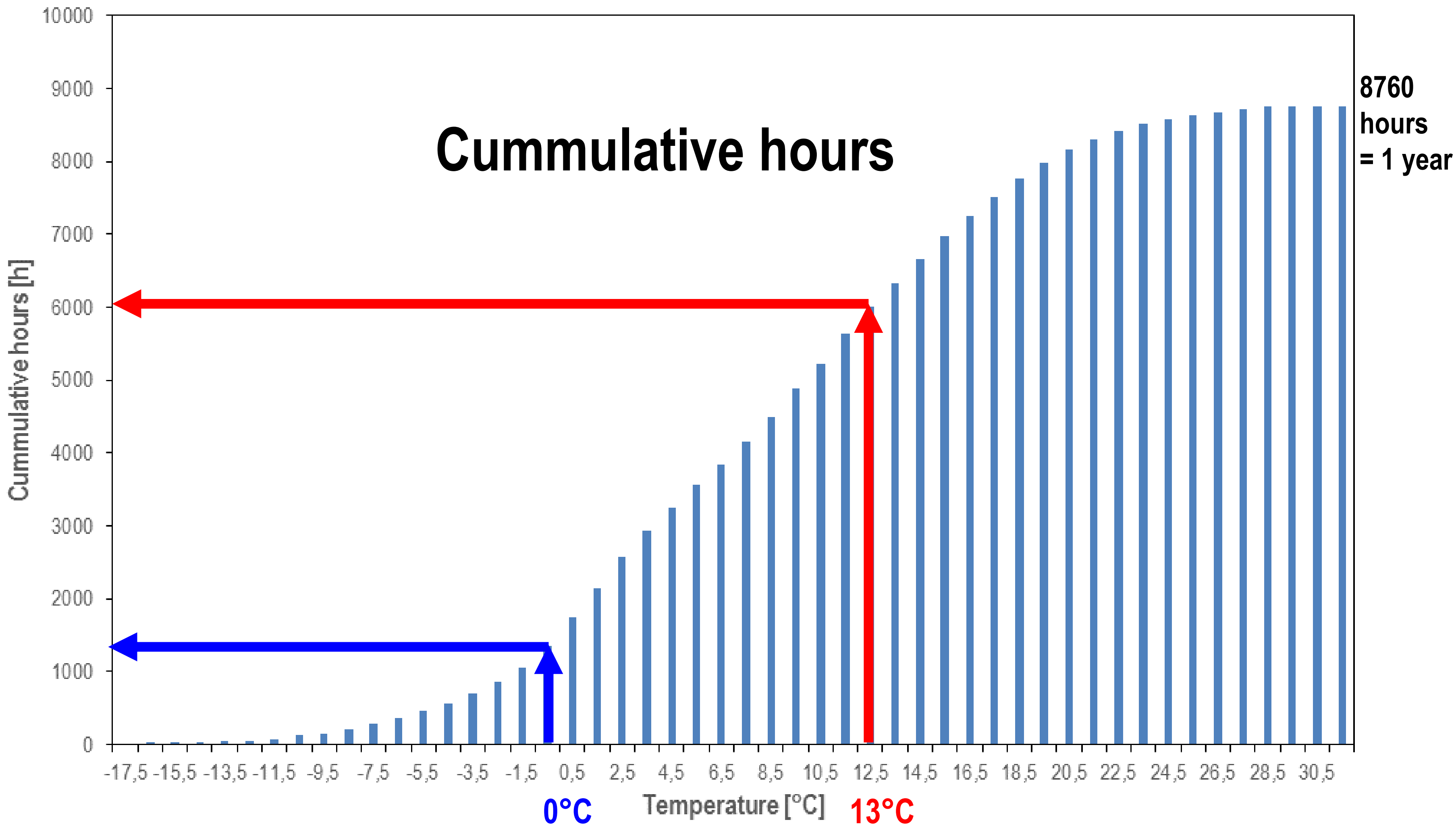
heating season data



Prague: temperature histogram



Prague: temperature histogram



Prague: temperature histogram

Degree-Hours, room temperature +20°C,

te,lim,d,j	te,lim,h,j	te,m,j	tj τ_j	cummulative tkum,j	DH20/13	cummulative DH20/13,kum	fraction fSH	fHW
-18	-17	-17,5	0	0	0	0	0,000	0,000
-17	-16	-16,5	5	5	183	183	0,002	0,001
-16	-15	-15,5	5	10	178	360	0,002	0,001
-15	-14	-14,5	14	24	483	843	0,005	0,002
-14	-13	-13,5	14	38	469	1312	0,005	0,002
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				0,037
14	15	14,5	326	6656				0,037
15	16	15,5	320	6976				0,037
16	17	16,5	273	7249				0,031
27	28	27,5	38	8720				0,004
28	29	28,5	30	8750				0,003
29	30	29,5	6	8756				0,001
30	31	30,5	4	8760				0,000
31	32	31,5	0	8760				0,000
			8760				**1,000**	**1,000**

heating season

season lasts until the ambient emperature +13°C

95816 = degree-hours/season

summer

hours/year

Degree-Hours room temperature +20°C

In the bin j :

$$DH_j = (t_i - t_{e,j}) \cdot \tau_j = (20 - 8{,}5) \cdot 334 = 3841 \text{ Kh}$$

DH_j … degree-hours in bin j

t_i … room temperature
$t_{e,j}$ … mean ambient temp.
$\tau_{e,j}$ … bin duration (hours)

fraction:

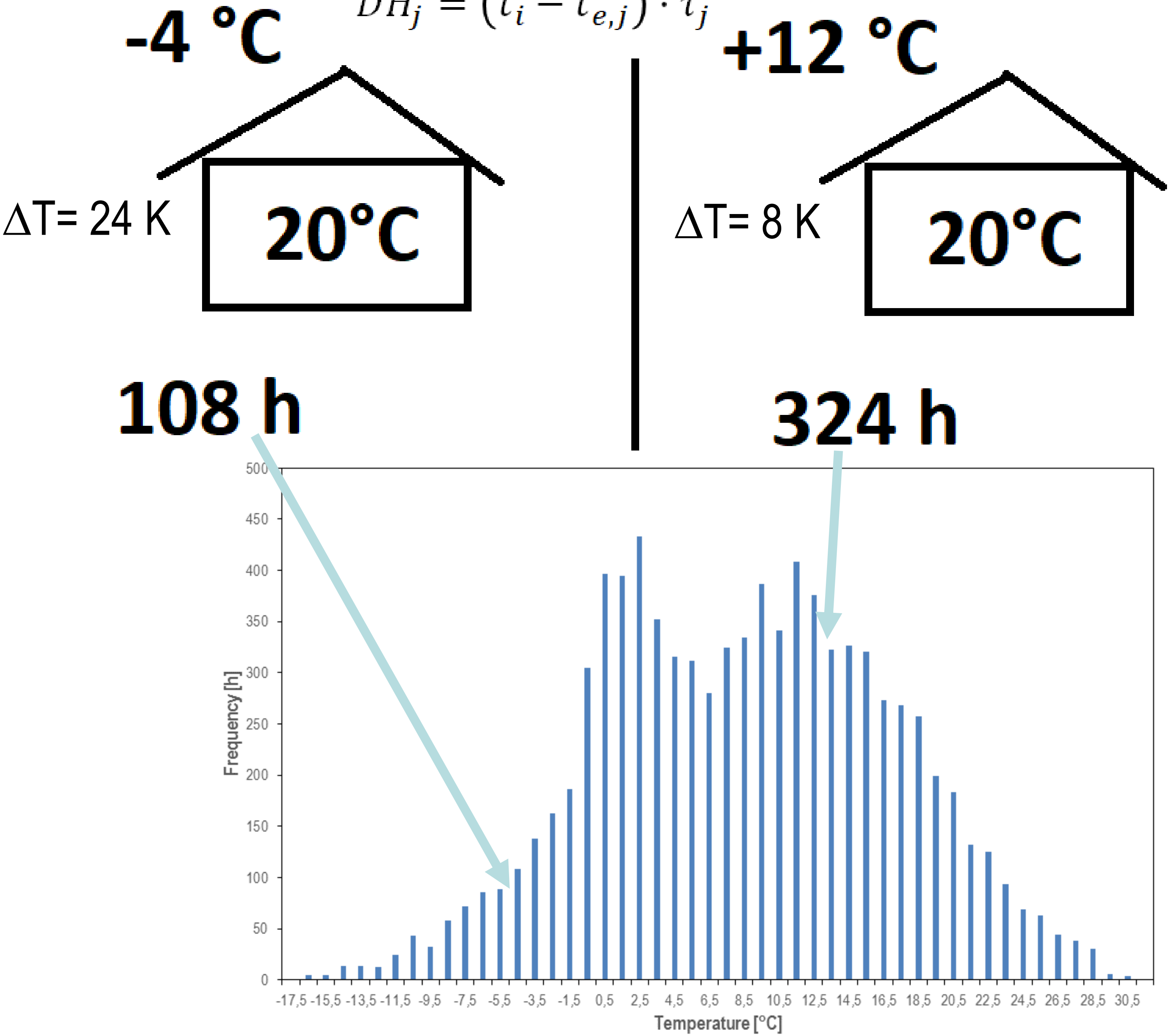
$$f_{SH} = \frac{DH_j}{\sum_j DH_j} = \frac{3841}{95816} = 0{,}040$$

DH_j … degree-hours in bin j

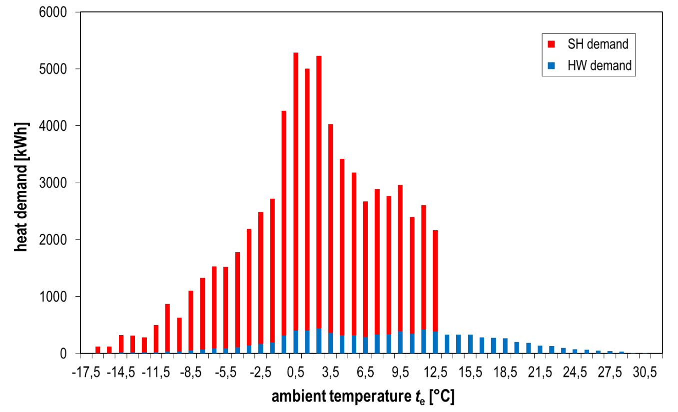
ΣDH_j … degree-hours in season

te,m,j	tj τ_j	cummulative tkum,j	DH20/13	cummulative DH20/13,kum	fraction fSH	fHW
-17,5	0	0	0	0	0,000	0,0
-16,5	5	5	183	183	0,002	0,0
-15,5	5	10	178	360	0,002	0,0
-14,5	14	24	483	843	0,005	0,0
-13,5	14	38	469	1312	0,005	0,0
8,5	334	4496	3841	82225	0,040	0,0
9,5	387	4883	4064	86289	0,042	0,0

$$DH_j = (t_i - t_{e,j}) \cdot \tau_j$$



Bin method:



inputs

Heat source temperature (ground, air,..)

Equithermal temperature of water

Energy balance

outputs

annual results

Energy balance

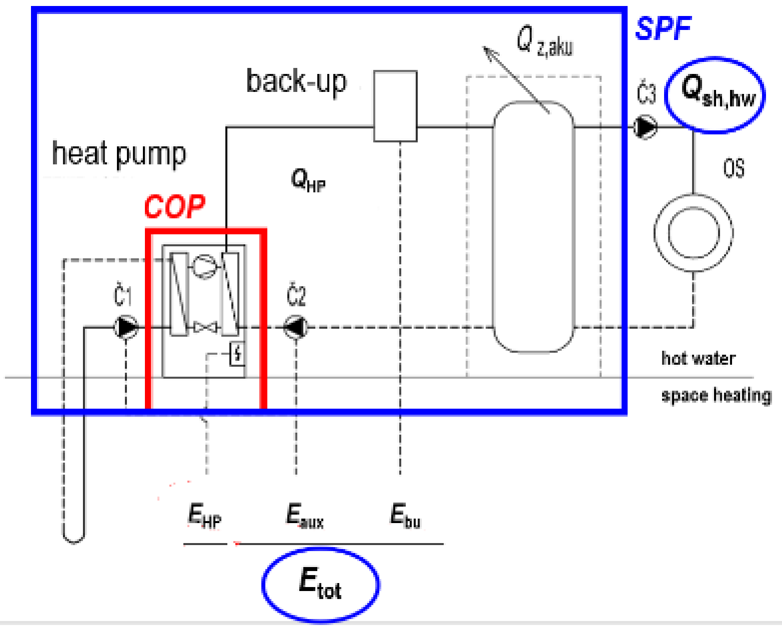
- **for each temperature bin is determined (for given mean temperature of the bin)**
  - heat demand for the building
  - heat output from HP / energy from HP available
  - heat delivered by HP to cover heat demand
  - electricity demanded by compressor
  - heat delivered by back-up heater (electricity)
  - operation time of HP
  - consumption of auxiliary energy (pumps)

Bin method: annual results

seasonal performance factor

$$SPF = \frac{Q_{\mathrm{HP,delivered}} + Q_{bu}}{E_{\mathrm{HP}} + E_{\mathrm{bu}} + E_{\mathrm{aux}}}$$

$$SPF = \frac{Q_{\mathrm{sh,hw}}}{E_{\mathrm{tot}}}$$



Bin method: **annual** results

total delivered energy by heat pump $$Q_{\mathrm{HP,delivered}} = \sum_j Q_{\mathrm{HP,delivered,\,j}}$$

total electricity for heat pump $$E_{\mathrm{HP}} = \sum_j E_{\mathrm{HP,j}}$$

total electricity for back up heater $$E_{\mathrm{bu}} = \sum_j E_{\mathrm{bu,j}}$$

total electricity for auxiliaries $$E_{\mathrm{aux}} = \sum_j E_{\mathrm{aux,j}}$$

Bin method: inputs

- **space heating demand – distribution to bins**
  - simplified method, based on degree-hours DH_j in the bin
  - calculation based on:

    total space heating demand $\boldsymbol{Q_{SH}} \sim \boldsymbol{DH}$ in the given period (season)

In the bin j :

$$Q_{SH,j} = Q_{SH} \frac{DH_j}{DH} = Q_{SH} \frac{(t_i - t_{e,j}) \cdot \tau_j}{\sum_j DH_j} = Q_{SH} \cdot f_{SH}$$

$\boldsymbol{Q_{SH}}$ … total space heating demand
$\boldsymbol{DH_j}$ … degree-hours in bin j
$\boldsymbol{DH}$ … degree-hours in season

$\boldsymbol{t_i}$ … room temperature
$\boldsymbol{t_{e,j}}$ … mean ambient temp.
$\boldsymbol{\tau_{e,j}}$ … bin duration (hours)
$\boldsymbol{\Sigma DH_j}$ … degree-hours in season

$\boldsymbol{f_{SH}}$ … fraction

Bin method: inputs

In the bin j :

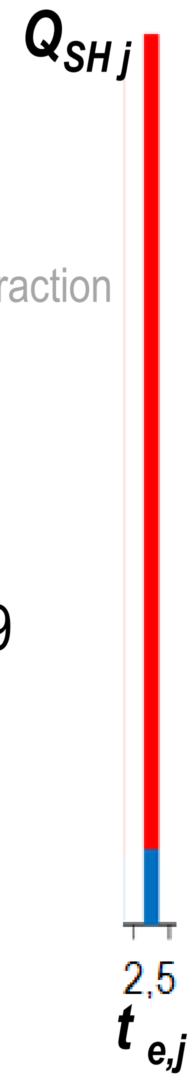
$$Q_{SH,j} = Q_{SH}\frac{DH_j}{DH} = Q_{SH}\frac{(t_i - t_{e,j})\cdot\tau_j}{\sum_j DH_j} = Q_{SH}\cdot f_{SH}$$

Q_{SH} … total space heating demand
DH_j … degree-hours in bin j
DH … degree-hours in season

t_i … room temperature
$t_{e,j}$ … mean ambient temp.
$\tau_{e,j}$ … bin duration (hours)
ΣDH_j … degree-hours in season

f_{SH} … fraction

$$Q_{SH,j} = Q_{SH}\frac{(t_i - t_{e,j})\cdot\tau_j}{\sum_j DH_j} = Q_{SH}\frac{(20°C - 2{,}5°C)\cdot 433h}{95816} = Q_{SH}\ .\ 0{,}079$$



Bin method: inputs

- **hot water demand – distribution to bins**
  - simple, based on hours H_j in the bin
  - total hot water demand $\boldsymbol{Q_{HW} \sim H}$ in the given period (= 8760 h = 1 year)

$$Q_{HW,j} = Q_{HW} \frac{H_j}{H} = Q_{HW} \frac{H_j}{\sum_j H_j} = Q_{HW} \cdot f_{HW}$$

Prague: temperature histogram

temperature			hours		degree-hours DH_j		fraction	
from	to	**mean**	per bin	cumulative	per bin	cumulative	space heating	hot water
te,lim,d,j	**te,lim,h,j**	**te,m,j**	**tj** τ_j	**tkum,j**	**DH20/13**	**DH20/13,kum**	**fSH**	**fHW**
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
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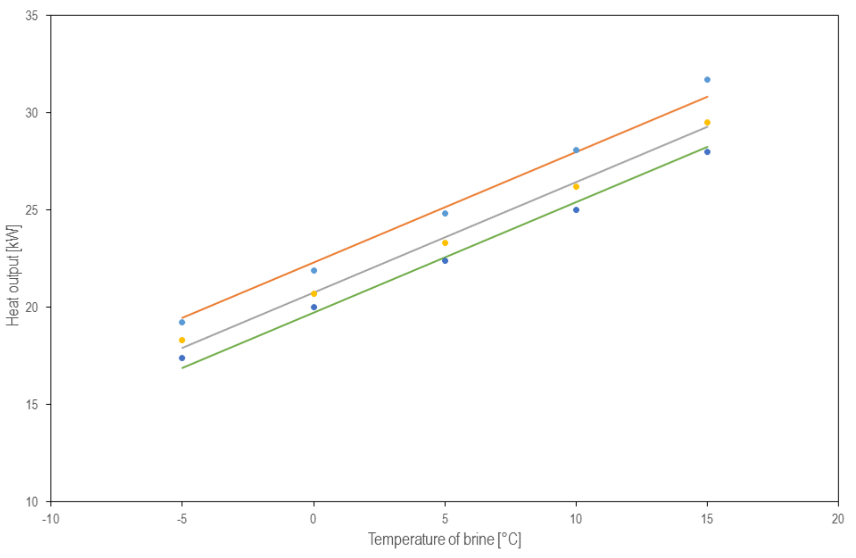
12	13	12,5	376	6008	2820	95816	0,029	0,043
13	14	13,5	322	6330				0,037
14	15	14,5	326	6656		95816 = degree-hours/season		0,037
15	16	15,5	320	6976				0,037
16	17	16,5	273	7249				0,031
27	28	27,5	38	8720				0,004
28	29	28,5	30	8750				0,003
29	30	29,5	6	8756				0,001
30	31	30,5	4	8760				0,000
31	32	31,5	0	8760				0,000
			8760				**1,000**	**1,000**

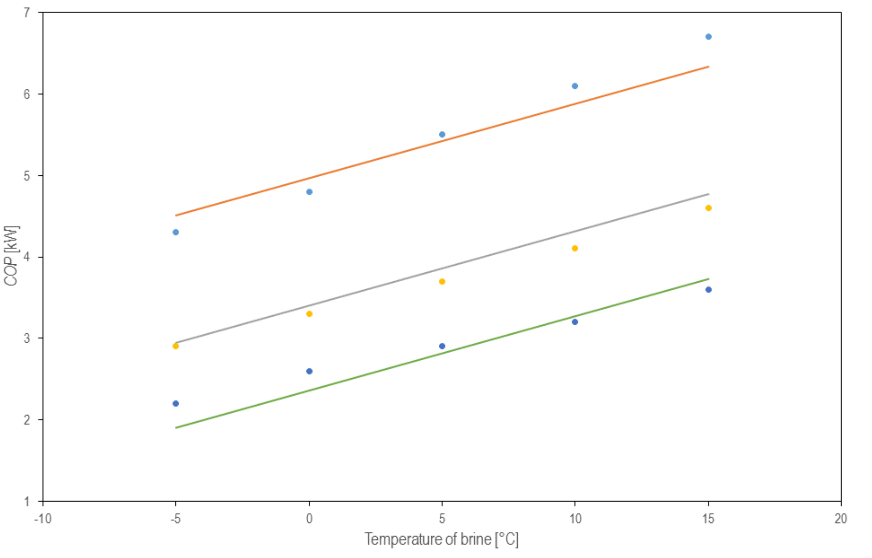
hours/year

Bin method: inputs

- **heat pump characteristics**

$Q_{HP} = f\,(t_{v1}, t_{k2})$, $COP = f\,(t_{v1}, t_{k2})$





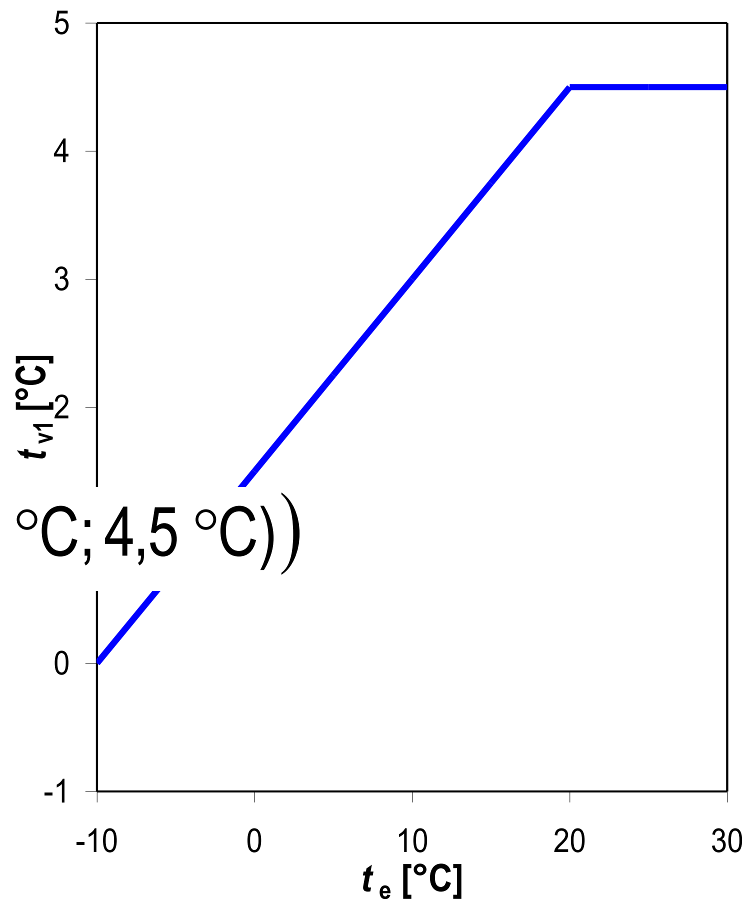
utilization of linear or quadratic interpolation and extrapolation of the heat pump characteristics for other operation conditions

$$\dot{Q}_{HP} = A + B \cdot t_{v1} + C \cdot t_{k2} + D \cdot t_{v1}^2 + E \cdot t_{k2}^2 + F \cdot t_{v1} \cdot t_{k2}$$

$$COP = a + b \cdot t_{v1} + c \cdot t_{k2} + d \cdot t_{v1}^2 + e \cdot t_{k2}^2 + f \cdot t_{v1} \cdot t_{k2}$$

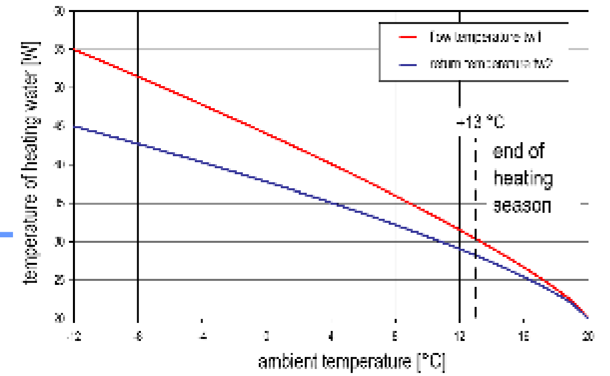
Bin method: inputs

- **heat source temperature** = temperature at the input to evaporator t_{v1}
  - air-water: $t_{v1} = t_e$
  - water-water: $t_{v1} = 10\ °C$
  - ground-water. $t_{v1} = f(t_e)$



EN 15316-4-2:

$$t_{v1} = \max\left(0\ °C; \min\left(0{,}15 \cdot t_e + 1{,}5\ °C; 4{,}5\ °C\right)\right)$$

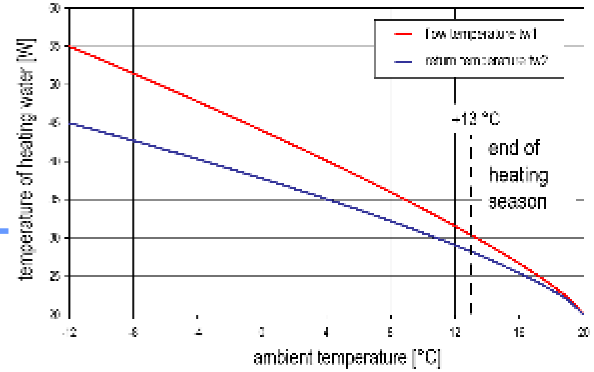


Bin method: inputs

- **heating water temperature = f (t_e)**
  - equithermal **flow** temperature of heating water $t_{k2} = t_{w1} + 3\,\mathrm{K}$
  - design temperatures flow/return $t_{w1,N}$ / $t_{w2,N}$
  - design ambient temperature $t_{e,N}$
  - design room temperature $t_{i,N}$ = average indoor temperature t_i
  - calculation of heating water temperature from equation for heat output of heating body

$$\frac{\dot{Q}_z}{\dot{Q}_{z,N}} = \left(\frac{\Delta t}{\Delta t_N}\right)^n \qquad \frac{\dot{Q}_z}{\dot{Q}_{z,N}} = \frac{t_i - t_e}{t_{i,N} - t_{e,N}} \qquad \dot{m} = \dot{m}_N$$

Equithermal temperature of water

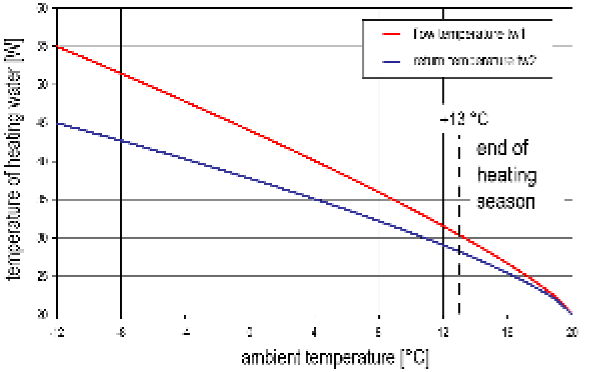


$$\dot{m} = \dot{m}_N \longrightarrow \frac{\dot{Q}}{c(t_{w1} - t_{w2})} = \frac{\dot{Q}_N}{c(t_{w1,N} - t_{w2,N})}$$

$$\frac{t_{w1} - t_{w2}}{t_{w1,N} - t_{w2,N}} = \frac{\dot{Q}}{\dot{Q}_N} = \frac{t_i - t_e}{t_{i,N} - t_{e,N}}$$

$$t_{w1} - t_{w2} = (t_{w1,N} - t_{w2,N})\frac{t_i - t_e}{t_{i,N} - t_{e,N}}$$

Equithermal temperature of water



$$\frac{\dot{Q}_z}{\dot{Q}_{z,N}} = \left(\frac{\Delta t}{\Delta t_N}\right)^n = \left(\frac{\frac{t_{w1}+t_{w2}}{2} - t_i}{\frac{t_{w1,N}+t_{w2,N}}{2} - t_{i,N}}\right)^n = \frac{t_i - t_e}{t_{i,N} - t_{e,N}}$$

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

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

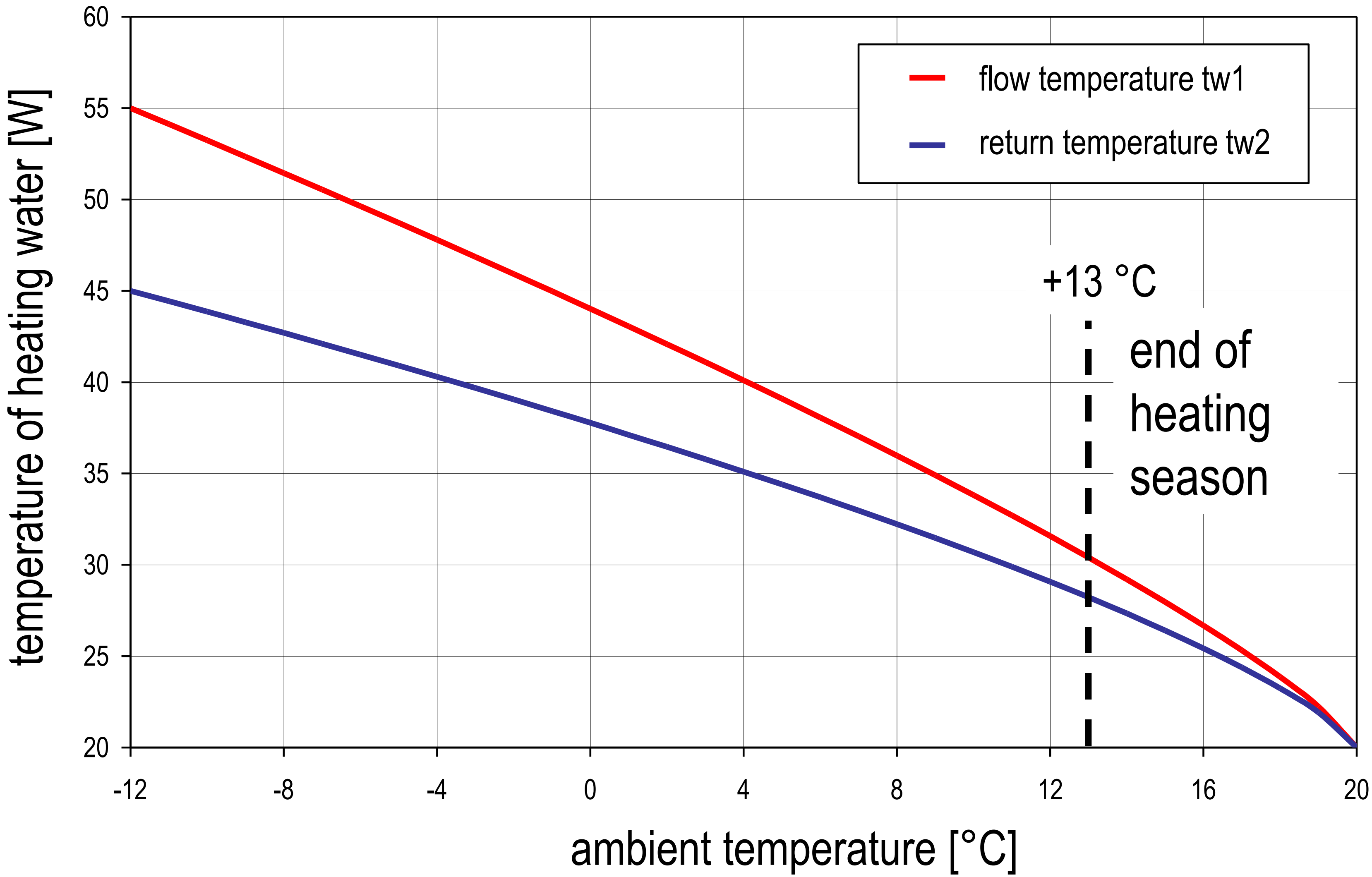
$$t_{w1} = t_i + \frac{t_{w1,N} - t_{w2,N}}{2}\cdot\frac{t_i - t_e}{t_i - t_{e,N}} + \left(\frac{t_{w1,N}+t_{w2,N}}{2} - t_i\right)\cdot\left(\frac{t_i - t_e}{t_i - t_{e,N}}\right)^{1/n}$$

n ... temperature exponent

n = 1,3 heating body

n = 1,1 floor heating

Equithermal temperature of heating water



Energy balance

- **for each temperature bin is calculated (for given mean temperature of the bin)**
  1. heat demand for the building
  2. heat output from HP / energy from HP available
  3. heat supplied by HP (heat demand coverage)
  4. electricity consumed by HP
  5. heat supplied by back-up
  6. operation time of HP
  7. consumption of auxiliary energy (pumps)

Bin method: **outputs**

1. Heat demand for the building [kWh] $Q_{SH,j} = Q_{SH} \cdot f_{SH}$

2. available energy from HP [kWh] $Q_{HP,available,j} = \dot{Q}_{HP,j} \cdot \tau_j$

3. heat supplied by HP to cover demand [kWh] $Q_{HP,delivered,j} = \min(Q_{HP,available}; Q_{SH,HW})_j$

4. electricity consumed by heat pump [kWh] $E_{HP,j} = \dfrac{Q_{HP,delivered,j}}{COP_j}$

Bin method: **outputs**

5. heat supplied by back-up heater
   electricity use of electroboiler [kWh]

$$E_{bu,j} = Q_{SH,HW,j} - Q_{HP,delivered,j}$$

6. operation time of heat pump

$$\tau_{HP,j} = \frac{Q_{HP,delivered,j}}{\dot{Q}_{HP,j}}$$

7. auxiliary energy consumption
   (pumps, valves, etc)

$$E_{aux,j} = P_{aux} \cdot \tau_{HP,j}$$

Bin method: **annual** results

total delivered energy by heat pump $$Q_{\mathrm{HP,delivered}} = \sum_j Q_{\mathrm{HP,delivered},j}$$

total electricity for heat pump $$E_{\mathrm{HP}} = \sum_j E_{\mathrm{HP},j}$$

total electricity for back up heater $$E_{\mathrm{bu}} = \sum_j E_{\mathrm{bu},j}$$

total electricity for auxiliaries $$E_{\mathrm{aux}} = \sum_j E_{\mathrm{aux},j}$$

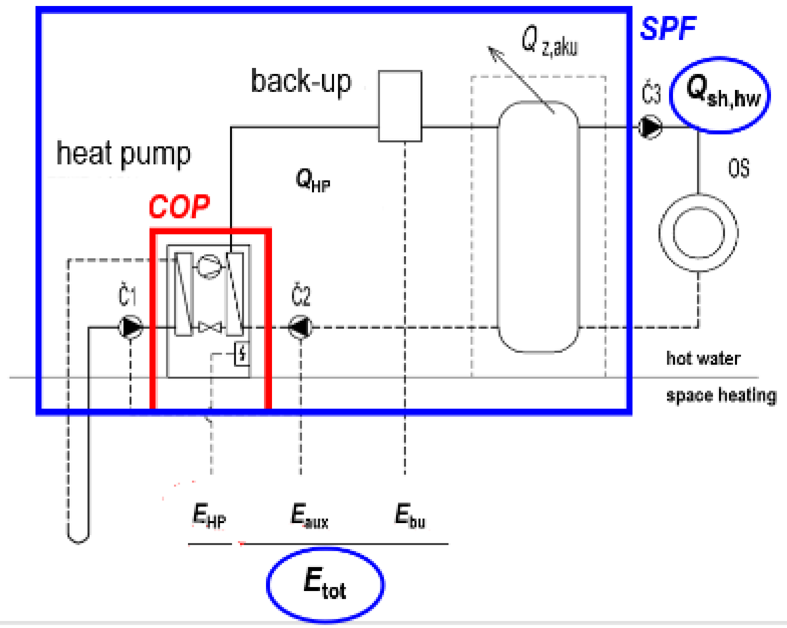
total operation time of heat pump $$\tau_{\mathrm{HP}} = \sum_j \tau_{\mathrm{HP},j}$$

Bin method: annual results

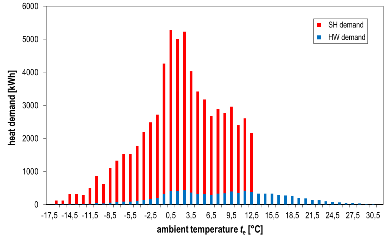
seasonal performance factor

$$SPF = \frac{Q_{\mathrm{HP,delivered}} + Q_{bu}}{E_{\mathrm{HP}} + E_{\mathrm{bu}} + E_{\mathrm{aux}}}$$

$$SPF = \frac{Q_{\mathrm{sh,hw}}}{E_{\mathrm{tot}}}$$



Example: family house, SH only



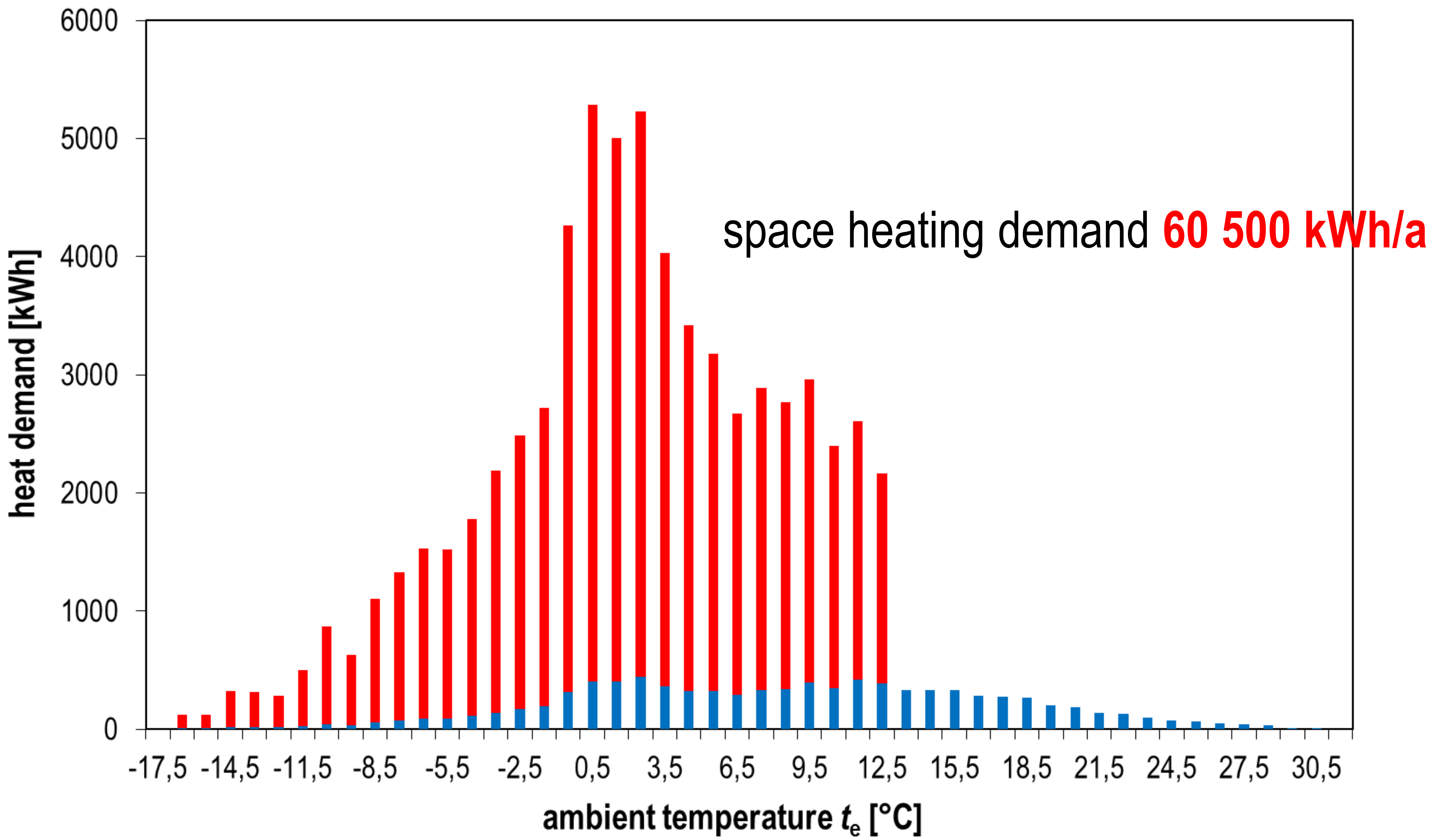
- **space heating**
  - heat loss 30 kW (-18 °C), ε = 0,8 [-]
  - climate defined by table, d = 235, $t_{e,m}$ = 3,0 °C

$$Q_{SH} = d \cdot 24 \cdot \varepsilon \cdot \dot{Q}_N \cdot \frac{\left(t_{i,m} - t_{e,m}\right)}{\left(t_{i,N} - t_{e,N}\right)}$$

Q_N [kW]	nominal (design) heat loss
$t_{i,N}$ [°C]	design indoor temperature
$t_{e,N}$ [°C]	design outdoor temperature
$t_{i,m}$ [°C]	average indoor temperature
$t_{e,m}$ [°C]	average outdoor temperature
ε [-]	correction factor

- space heating demand **60 500 kWh/a**
- heating system **50/40 °C**

Example: heat demand



Example: heat pump

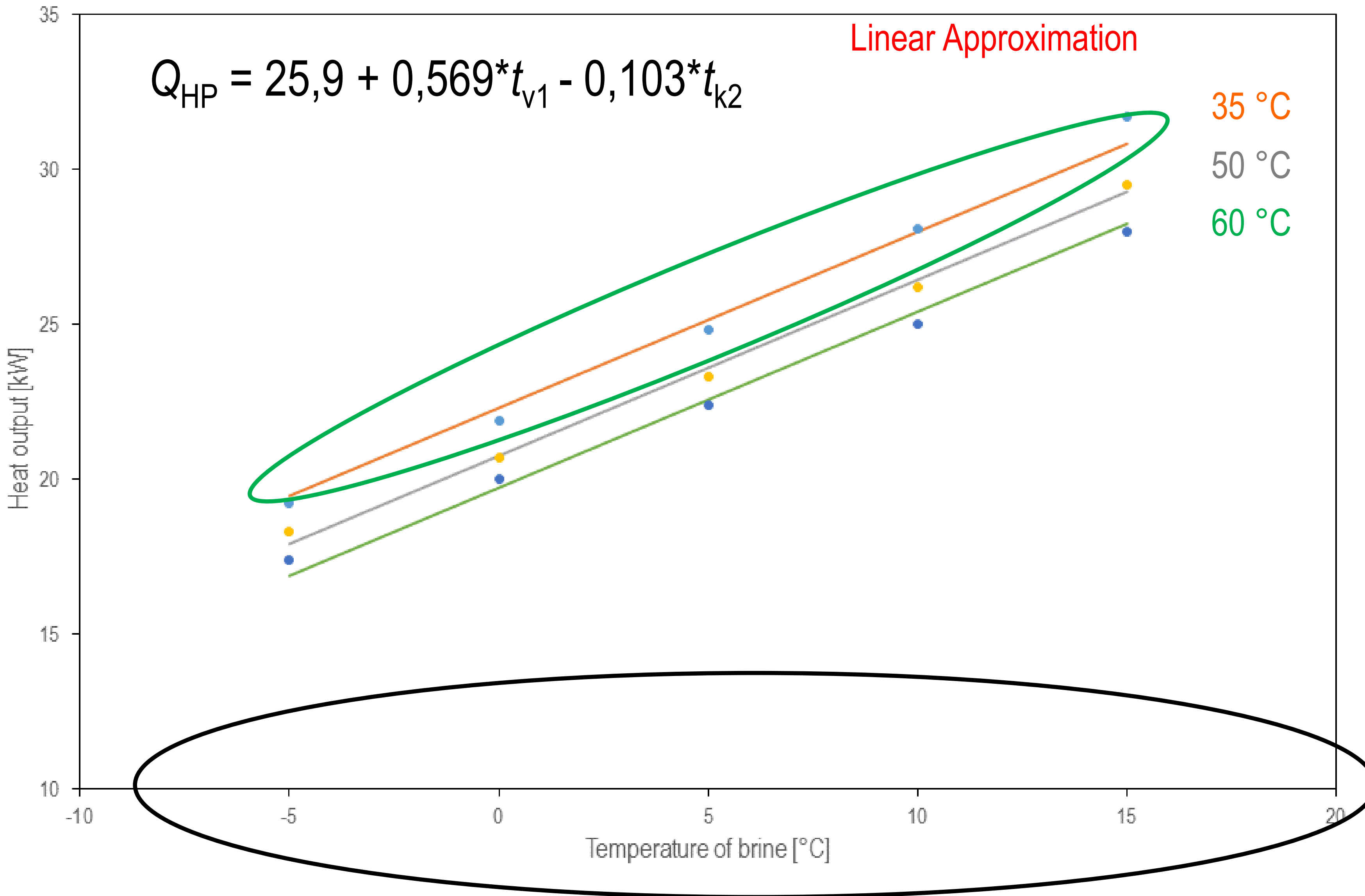
- **ground source heat pump type WPF 20**
  - nominal heat output Q_{HP} = 21,9 kW
  - COP = 4,8 B0/W35

Brine | water heat pump WPF 20

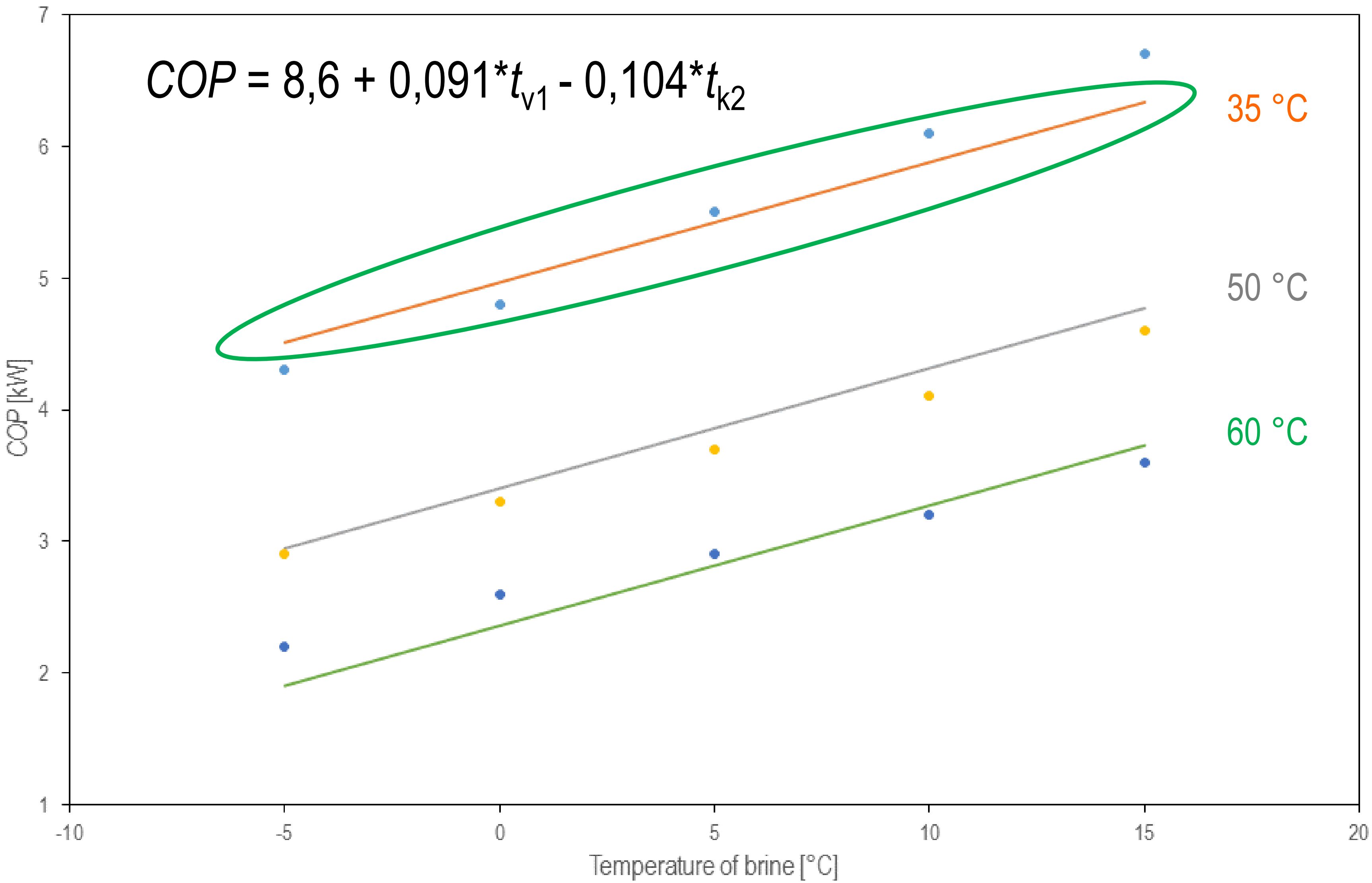
Heating output (kW), power consumption (kW) and coefficient of performance ε

Heat source temp. °C	Heating output			Power consumption			COP		
	35 °C	50 °C	60 °C	35 °C	50 °C	60 °C	35 °C	50 °C	60 °C
	kW	kW	kW	kW	kW	kW	ε	ε	ε
-5	19.2	18.3	17.4	4.5	6.4	7.8	4.3	2.9	2.2
0	21.9	20.7	20.0	4.5	6.3	7.8	4.8	3.3	2.6
+5	24.8	23.3	22.4	4.5	6.4	7.8	5.5	3.7	2.9
+10	28.1	26.2	25.0	4.6	6.4	7.8	6.1	4.1	3.2
+15	31.7	29.5	28.0	4.7	6.5	7.9	6.7	4.6	3.6
+20									

Example: heat pump



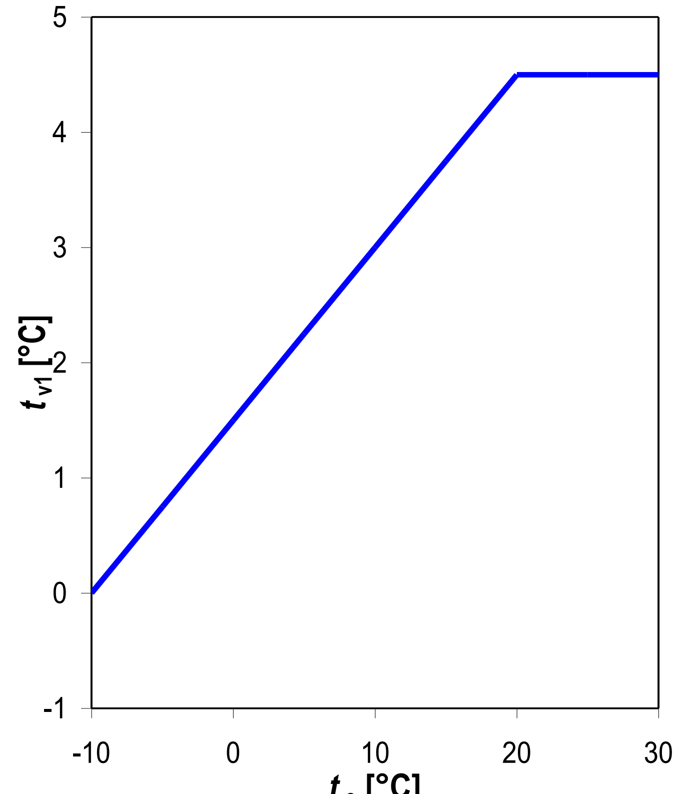
Example: heat pump



Example: boreholes

- **ground source**
  - input to evaporator dependent on ambient temperature

$$t_{v1} = \max\left(0\ °C; \min(0{,}15 \cdot t_e + 1{,}5\ °C; 4{,}5\ °C)\right)$$



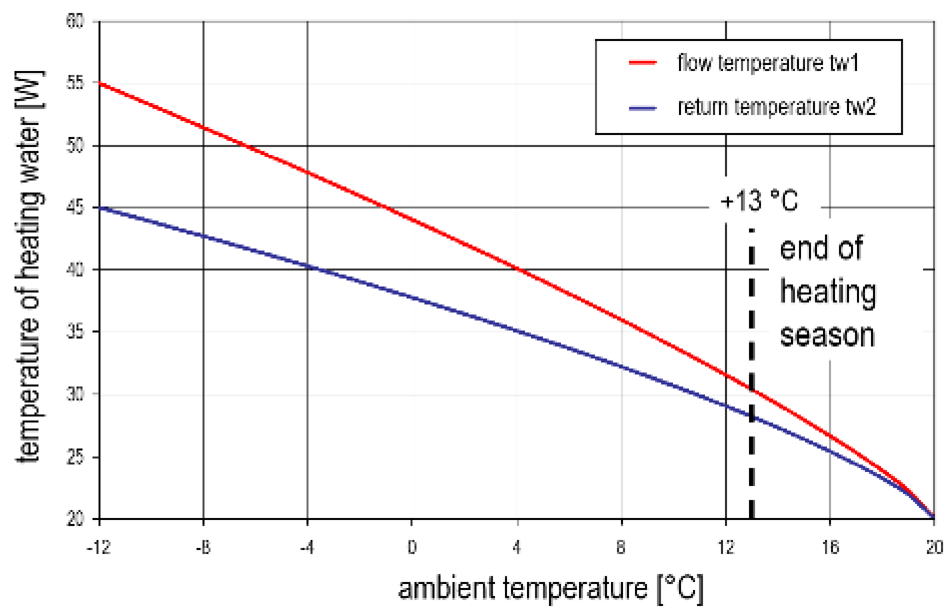
Example: heating system

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

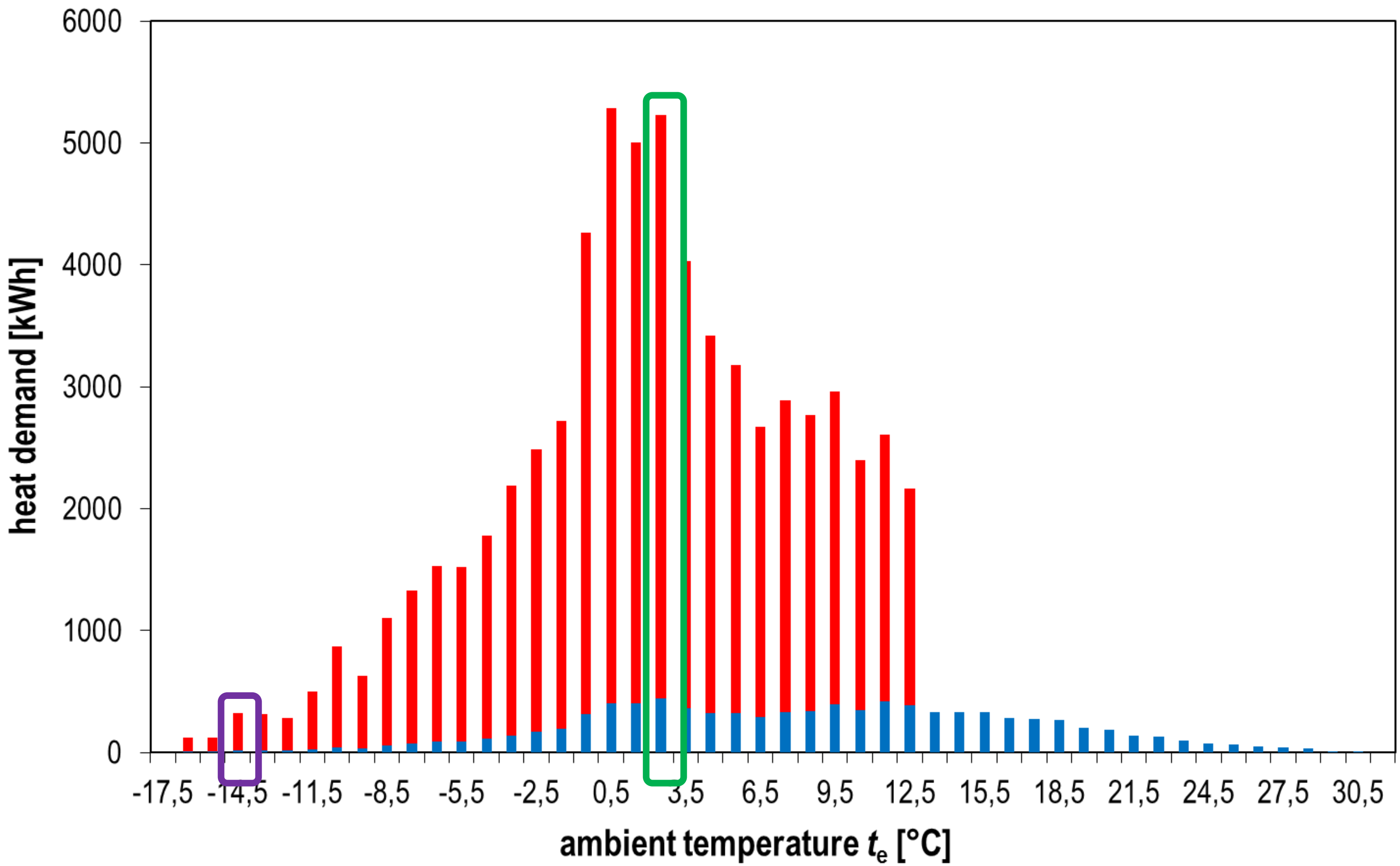
$$t_{w1} = t_i + \frac{t_{w1,N} - t_{w2,N}}{2} \cdot \frac{t_i - t_e}{t_i - t_{e,N}} + \left(\frac{t_{w1,N} + t_{w2,N}}{2} - t_i\right) \cdot \left(\frac{t_i - t_e}{t_i - t_{e,N}}\right)^{1/n}$$

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

weather compensation curve
(equi thermal)



Example: heat demand



space heating – example bin -14,5°C

- In the bin -14,5°C

$$Q_{SH,j} = Q_{SH}\frac{DH_j}{DH} = Q_{SH}\frac{\left(t_i - t_{e,j}\right)\cdot\tau_j}{\sum_j DH_j} = Q_{SH}\cdot f_{SH}$$

Q_{SH} … total space heating demand
DH_j … degree-hours in bin j
DH … degree-hours in season

t_i … room temperature
$t_{e,j}$ … mean ambient temp.
$\tau_{e,j}$ … bin duration (hours)
ΣDH_j … degree-hours in season

f_{SH} … fraction

$$Q_{SH,j} = 60500\frac{\left(20-\left(-14{,}5\right)\right)\cdot 14}{95816} = 60500\frac{483}{95816} = 305kWh$$

$$Q_{SH,j} = 60500\cdot 0{,}005 = 305kWh$$

Prague: temperature histogram

te,lim,d,j	te,lim,h,j	te,m,j	tj	tkum,j	DH20/13	DH20/13,kum	fSH	fHW
-18	-17	-17,5	0	0	0	0	0,000	0,000
-17	-16	-16,5	5	5	183	183	0,002	0,001
-16	-15	-15,5	5	10	178	360	0,002	0,001
-15	-14	-14,5	14	24	483	843	0,005	0,002
-14	-13	-13,5	14	38	469	1312	0,005	0,002
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				0,037
14	15	14,5	326	6656				0,037
15	16	15,5	320	6976				0,037
16	17	16,5	273	7249				0,031
27	28	27,5	38	8720				0,004
28	29	28,5	30	8750				0,003
29	30	29,5	6	8756				0,001
30	31	30,5	4	8760				0,000
31	32	31,5	0	8760				0,000
			8760			3992	**1,000**	**1,000**

Prague: temperature histogram

$t_{ed,j}$	$t_{eh,j}$	$t_{em,j}$	τ_j	$\tau_{kum,j}$	$DH_{20/13,j}$	$DH_{20/13,kum,j}$
°C	°C	°C	h	h	Kh	Kh
-18.0	-17.0	-17.5	0.0	0.0	0.0	0.0
-17.0	-16.0	-16.5	5.0	5.0	182.5	182.5
-16.0	-15.0	-15.5	5.0	10.0	177.5	360.0
-15.0	-14.0	-14.5	14.0	24.0	483.0	843.0
-14.0	-13.0	-13.5	14.0	38.0	469.0	1312.0
-13.0	-12.0	-12.5	13.0	51.0	422.5	1734.5
-12.0	-11.0	-11.5	24.0	75.0	756.0	2490.5
-11.0	-10.0	-10.5	43.0	118.0	1311.5	3802.0
-10.0	-9.0	-9.5	32.0	150.0	944.0	4746.0
-9.0	-8.0	-8.5	58.0	208.0	1653.0	6399.0
-8.0	-7.0	-7.5	72.0	280.0	1980.0	8379.0
-7.0	-6.0	-6.5	86.0	366.0	2279.0	10658.0
-6.0	-5.0	-5.5	89.0	455.0	2269.5	12927.5
-5.0	-4.0	-4.5	108.0	563.0	2646.0	15573.5
-4.0	-3.0	-3.5	138.0	701.0	3243.0	18816.5
-3.0	-2.0	-2.5	163.0	864.0	3667.5	22484.0
-2.0	-1.0	-1.5	186.0	1050.0	3999.0	26483.0
-1.0	0.0	-0.5	305.0	1355.0	6252.5	32735.5
0.0	1.0	0.5	396.0	1751.0	7722.0	40457.5
1.0	2.0	1.5	394.0	2145.0	7289.0	47746.5
2.0	3.0	2.5	433.0	2578.0	7577.5	55324.0
3.0	4.0	3.5	352.0	2930.0	5808.0	61132.0
4.0	5.0	4.5	316.0	3246.0	4898.0	66030.0
5.0	6.0	5.5	312.0	3558.0	4524.0	70554.0
6.0	7.0	6.5	280.0	3838.0	3780.0	74334.0
7.0	8.0	7.5	324.0	4162.0	4050.0	78384.0
8.0	9.0	8.5	334.0	4496.0	3841.0	82225.0
9.0	10.0	9.5	387.0	4883.0	4063.5	86288.5
10.0	11.0	10.5	341.0	5224.0	3239.5	89528.0
11.0	12.0	11.5	408.0	5632.0	3468.0	92996.0
12.0	13.0	12.5	376.0	6008.0	2820.0	95816.0
13.0	14.0	13.5	322.0	6330.0		

Example:
calculation bins:

$t_{em,j}$ = -14,5 °C

$t_{em,j}$ = 2,5 °C

Example calculation

$t_{em,j}$ = -14,5 °C

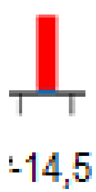
τ_j = 14 h

f_{SH} = 0,005 in table

$$Q_{SH,j} = 60500\frac{(20-(-14{,}5))\cdot 14}{95816} = 60500\frac{483}{95816} = 305 kWh$$

$$Q_{SH,j} = 60500\cdot 0{,}005 = 305 kWh$$

Q_{SH} = **305 kWh**



$t_{em,j}$ = 2,5 °C

τ_j = 433 h

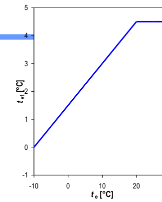
f_{SH} = 0,079

$$Q_{SH,j} = Q_{SH}\frac{DH_j}{DH} = Q_{SH}\frac{(t_i - t_{e,j})\cdot \tau_j}{\sum_j DH_j} = Q_{SH}\cdot f_{SH}$$

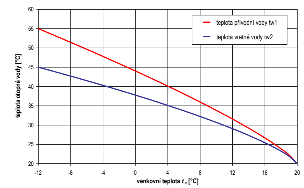
Q_{SH} = **4785 kWh**

Example calculation

t_{v1} = $$t_{v1} = \max\left(0\ °C; \min(0{,}15 \cdot t_e + 1{,}5\ °C; 4{,}5\ °C)\right)$$



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



n ... temperature exponent

n = 1,3 heating body

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

$Q_{HP,\mathbf{SH}}$ = $Q_{HP} = f\,(t_{v1}, t_{k2})$, $Q_{HP} = 25{,}9 + 0{,}569 * t_{v1} - 0{,}103 * t_{k2}$

$COP_{\mathbf{SH}}$ = $COP = f\,(t_{v1}, t_{k2})$ $COP = 8{,}6 + 0{,}091 * t_{v1} - 0{,}104 * t_{k2}$

Example calculation

t_{v1} =	0,0 °C	t_{v1} =	1,9 °C
$t_{k2,SH}$ =	50,7 °C	$t_{k2,SH}$ =	39,1 °C
$Q_{HP,SH}$ =	20,7 kW	$Q_{HP,SH}$ =	22,9 kW
COP_{SH} =	3,3	COP_{SH} =	4,7

Example calculation

$\tau_{HP,SH,avail}$ = … from table

$$Q_{HP,available,j} = \dot{Q}_{HP,j} \cdot \tau_j$$

2. available energy from HP [kWh]

$$Q_{HP,delivered,j} = \min(Q_{HP,available} ; Q_{SH,HW})_j$$

3. heat supplied by HP to cover demand [kW

$$E_{HP,j} = \frac{Q_{HP,delivered,j}}{COP_j}$$

4. electricity consumed by heat pump [kWh]

$$\tau_{HP,j} = \frac{Q_{HP,delivered,j}}{\dot{Q}_{HP,j}}$$

6. operation time of heat pump

$$E_{bu,j} = Q_{SH,HW,j} - Q_{HP,delivered,j}$$

5. heat supplied by back-up heater [kWh]

Example calculation

$\tau_{HP,SH,avail}$ =	**14 h**	$\tau_{HP,SH,avail}$ =	**433 h**
$Q_{HP,SH,avail}$ =	**289 kWh**	$Q_{HP,SH,avail}$ =	**9446 kWh**
$Q_{HP,SH,del}$ =	**289 kWh**	$Q_{HP,SH,del}$ =	**4785 kWh**
$E_{HP,SH}$ =	**83 kWh**	$E_{HP,SH}$ =	**1018 kWh**
$\tau_{HP,SH}$ =	**14 h** (only SH)	$\tau_{HP,SH}$ =	**209 h**
$Q_{bu,SH}$ =	**16 kWh**	$Q_{bu,SH}$ =	**0 kWh**

Bin method: annual results

total delivered energy by heat pump
$$Q_{\mathrm{HP,delivered}} = \sum_j Q_{\mathrm{HP,delivered,\,j}}$$

total delivered energy by back up heater
$$Q_{\mathrm{bu}} = \sum_j Q_{\mathrm{bu,\,j}}$$

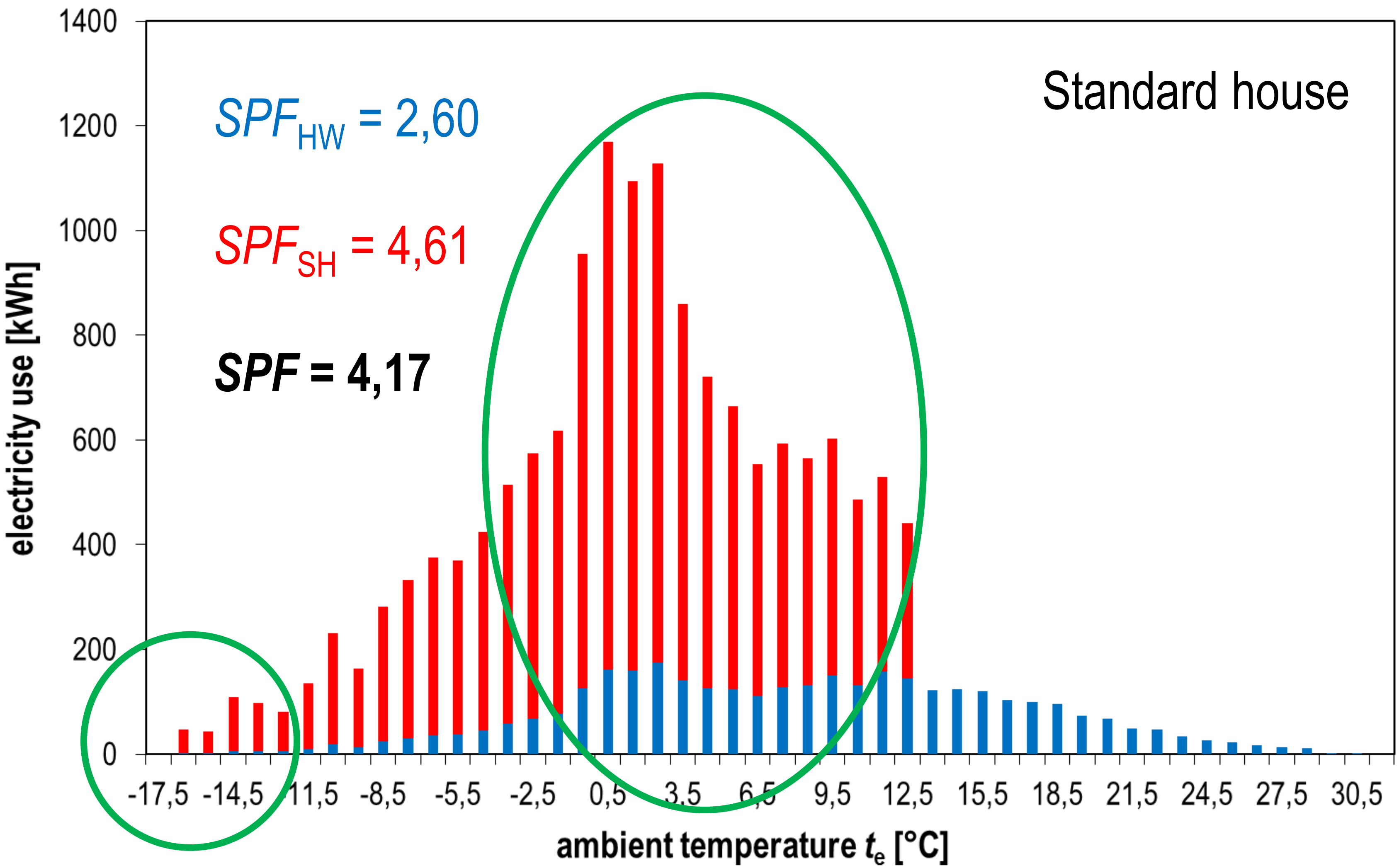
total electricity for heat pump
$$E_{\mathrm{HP}} = \sum_j E_{\mathrm{HP,j}}$$

total electricity for back up heater
$$E_{\mathrm{bu}} = \sum_j E_{\mathrm{bu,j}}$$

total electricity for auxiliaries
$$E_{\mathrm{aux}} = \sum_j E_{\mathrm{aux,j}}$$

seasonal performance factor
$$SPF = \frac{Q_{\mathrm{HP,delivered}} + Q_{bu}}{E_{\mathrm{HP}} + E_{\mathrm{bu}} + E_{\mathrm{aux}}}$$

Example calculation   Annual results



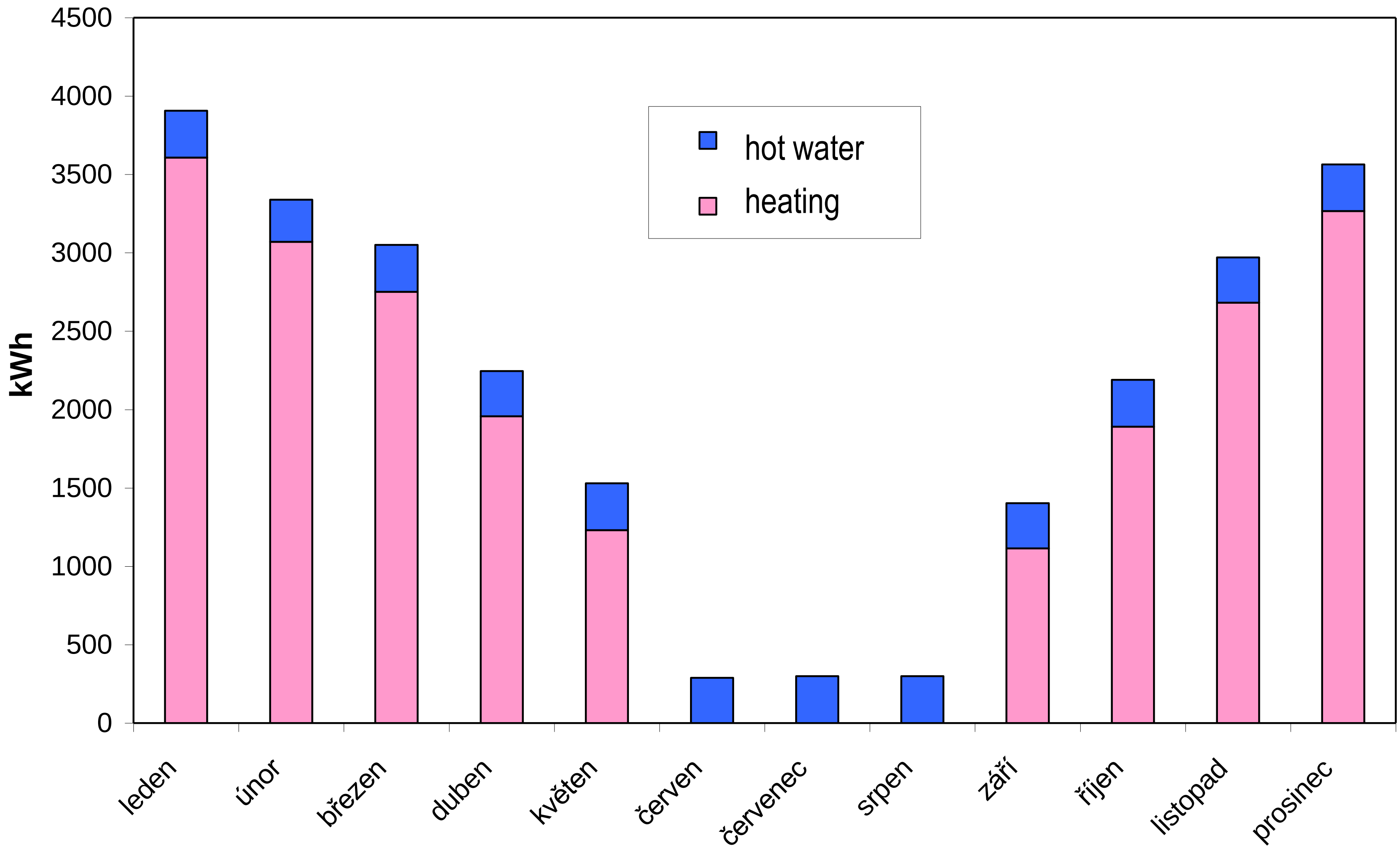
Standard house

Passive house

Standard house

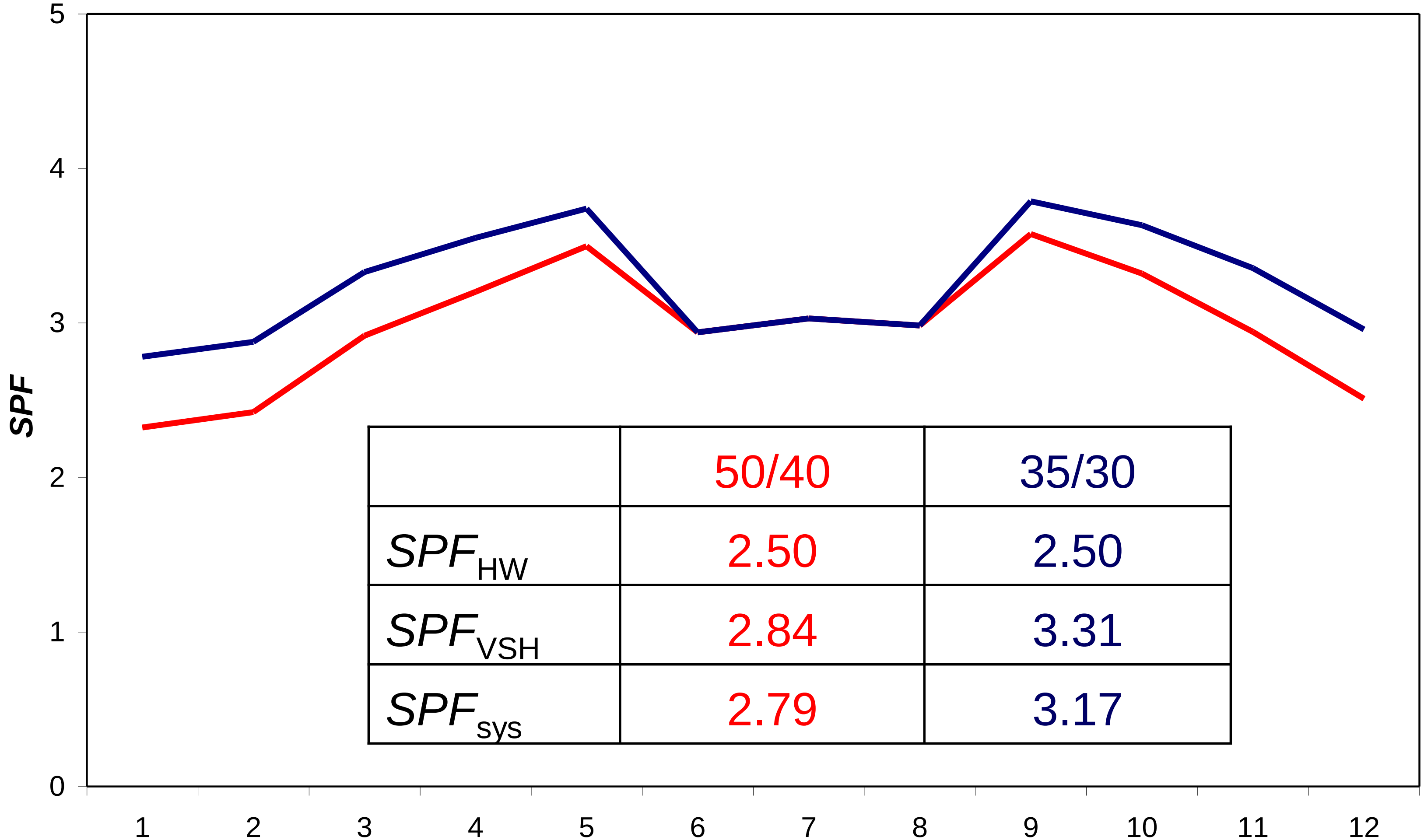
- **space heating**
  - 160 m^2
  - **heat loss 10 kW (-12 °C)**
  - **SH heat demand 21 500 kWh/a (135 kWh/m^2.a),**
  - typical meteorological year in Prague
  - heating system **50/40 °C** **35/30 °C**
- **hot water**
  - 4 persons, 45 l/per.day, heat losses 15 %
  - hot water temperature 55 °C, cold water temperature 15 °C
  - **hot water heat demand 3 500 kWh/a (14 % from total demand)**

Standard house



Heat pump air-water

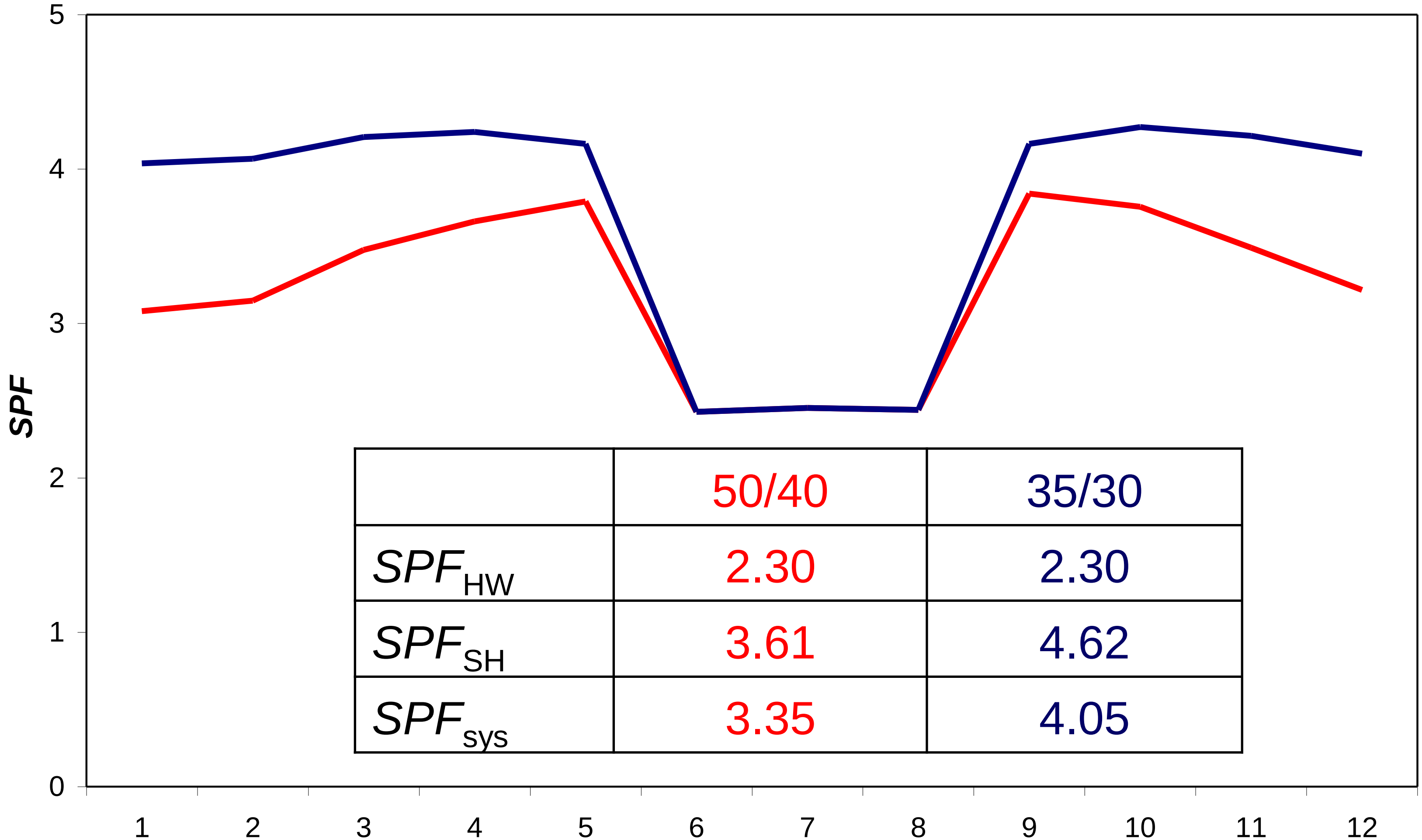
heat ouput 8,1 kW and *COP* = 3,4 … at A2/W35



	50/40	35/30
SPF_{HW}	2.50	2.50
SPF_{VSH}	2.84	3.31
SPF_{sys}	2.79	3.17

Heat pump ground-water

heat output 9,9 kW and *COP* = 4,5 … at B0/W35



	50/40	35/30
SPF_{HW}	2.30	2.30
SPF_{SH}	3.61	4.62
SPF_{sys}	3.35	4.05

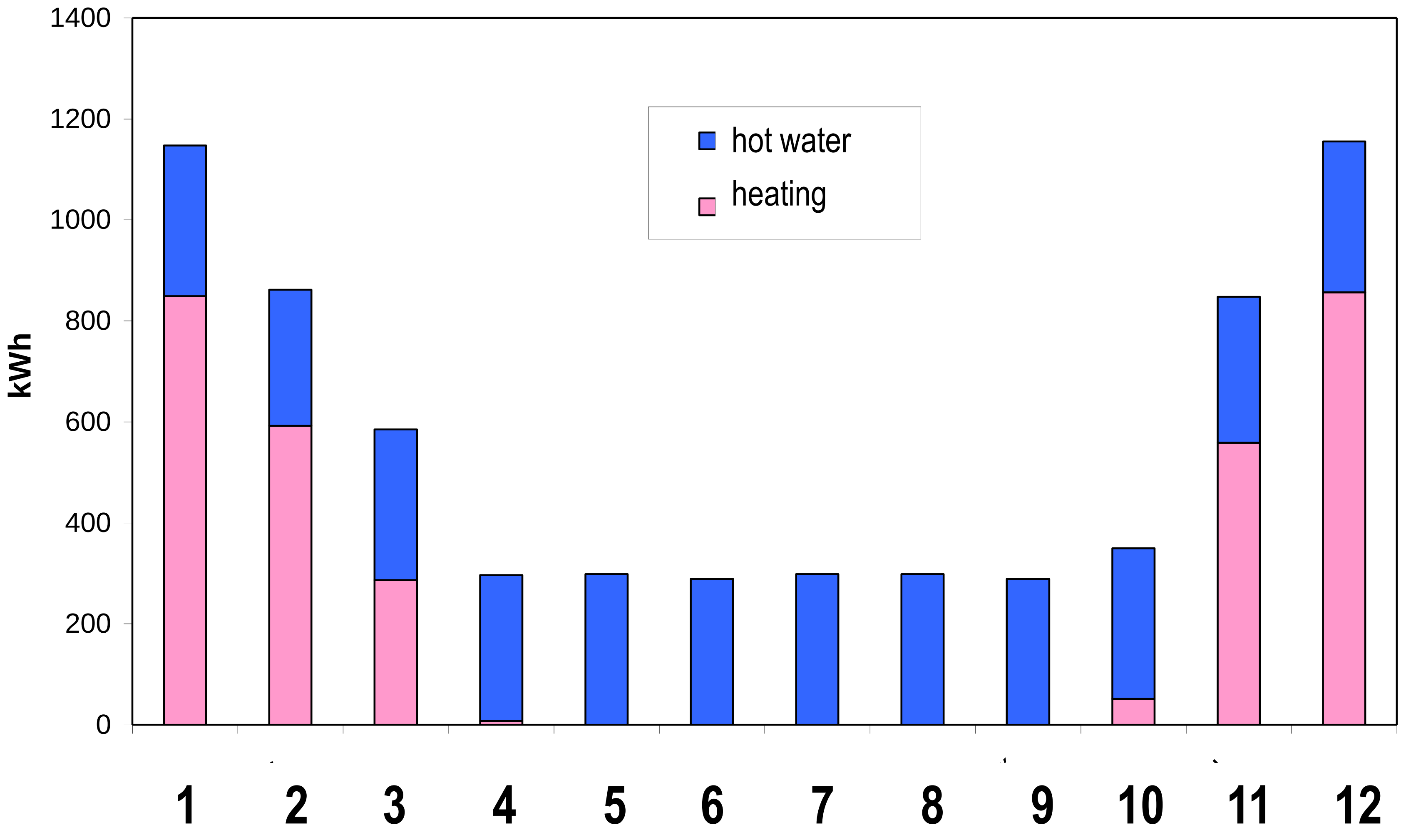
Standard house

- **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

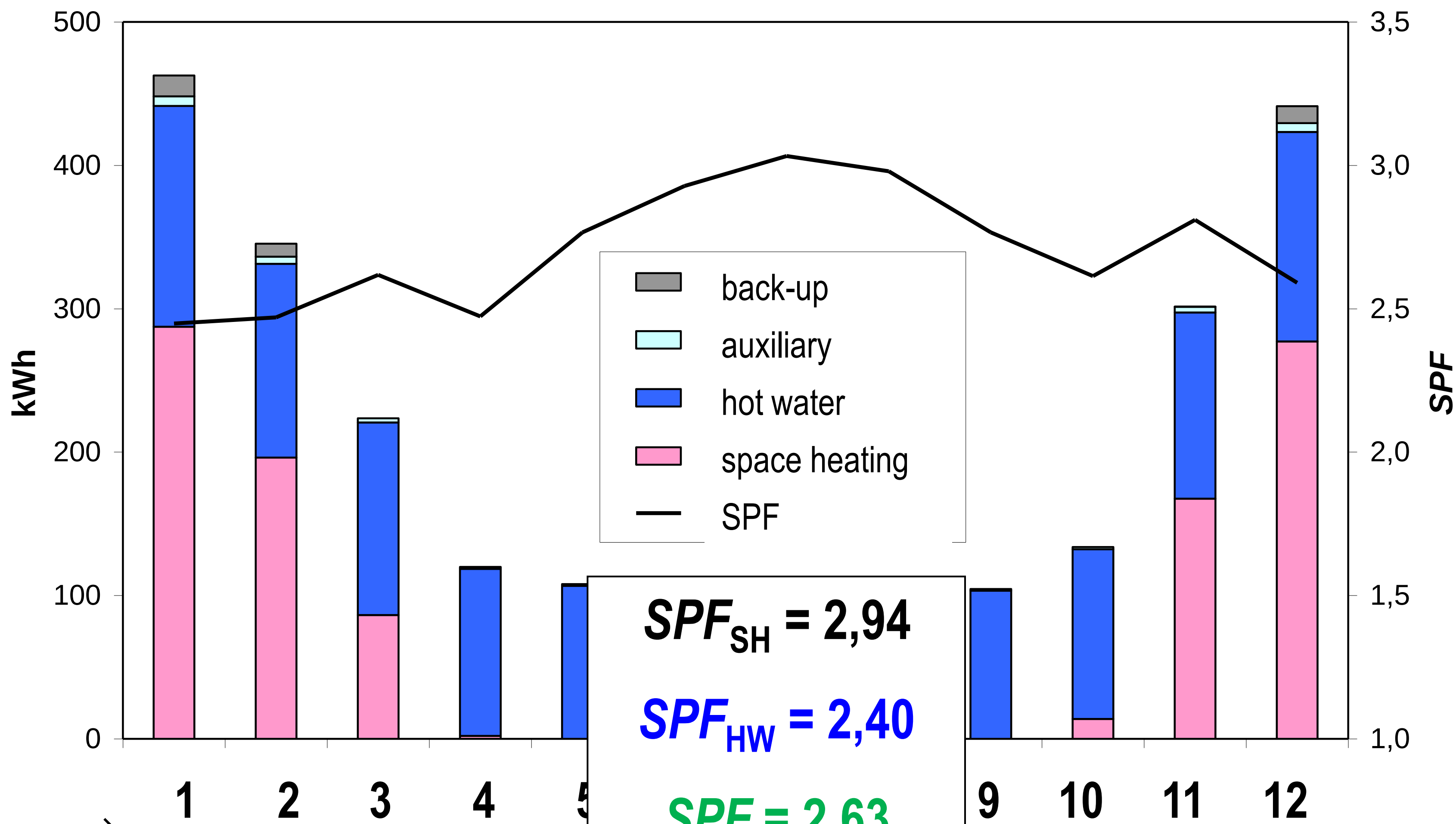
- **space heating**
  - 160 m²
  - **heat loss 2.7 kW (-12 °C)**
  - **SH heat demand 3 200 kWh/a (20 kWh/m².a),**
  - typical meteorological year in Prague
  - heating system **35/30 °C**
- **hot water**
  - 4 persons, 45 l/per.day, heat losses 15 %
  - hot water temperature 55 °C, cold water temperature 15 °C
  - hot water heat demand 3 500 kWh/a **(52 % from total demand)**

Passive house



Heat pump air-water

heat output 6,7 kW and *COP* = 3,2 …   at A2/W35



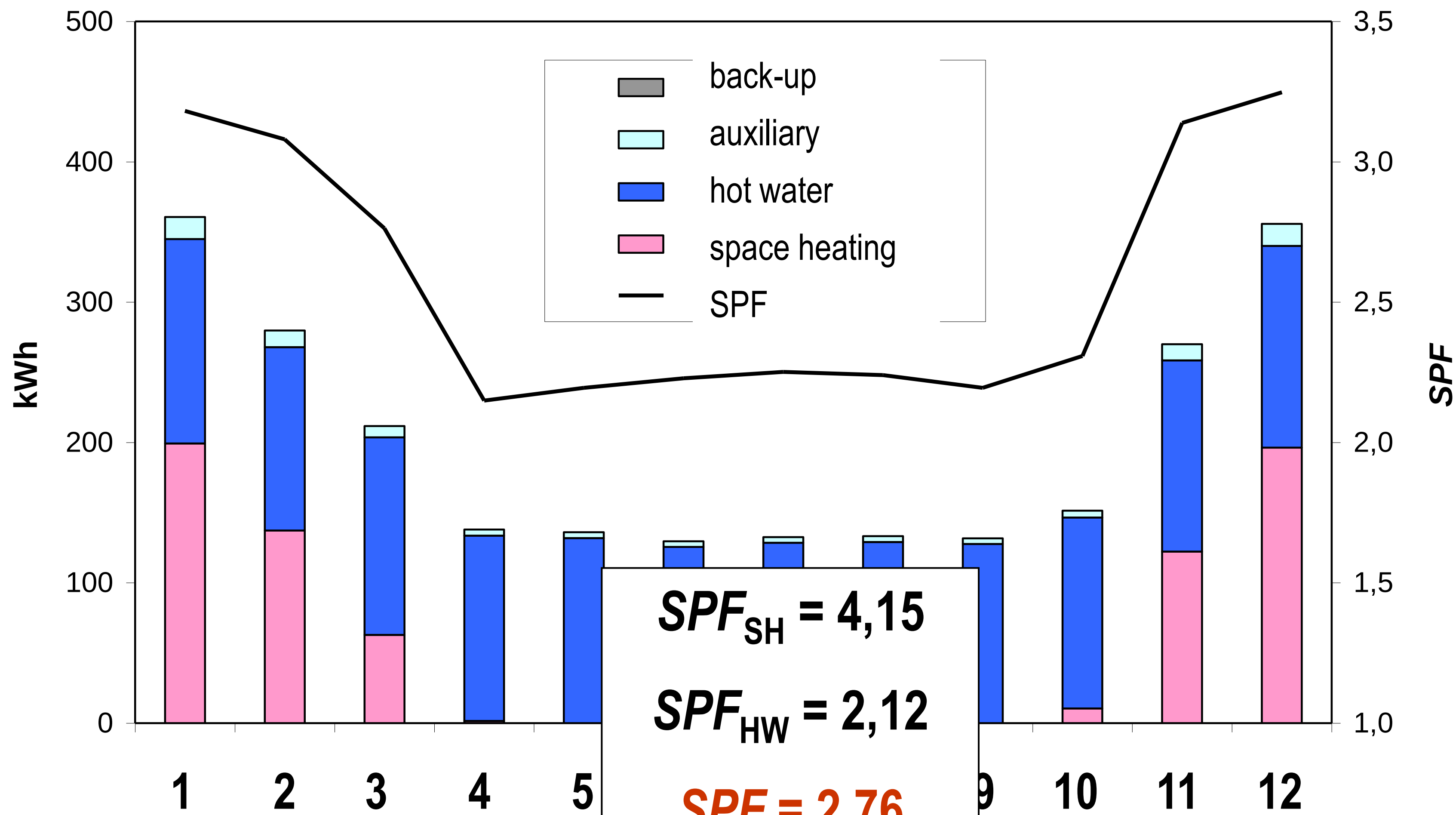
SPF_{SH} = 2,94

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