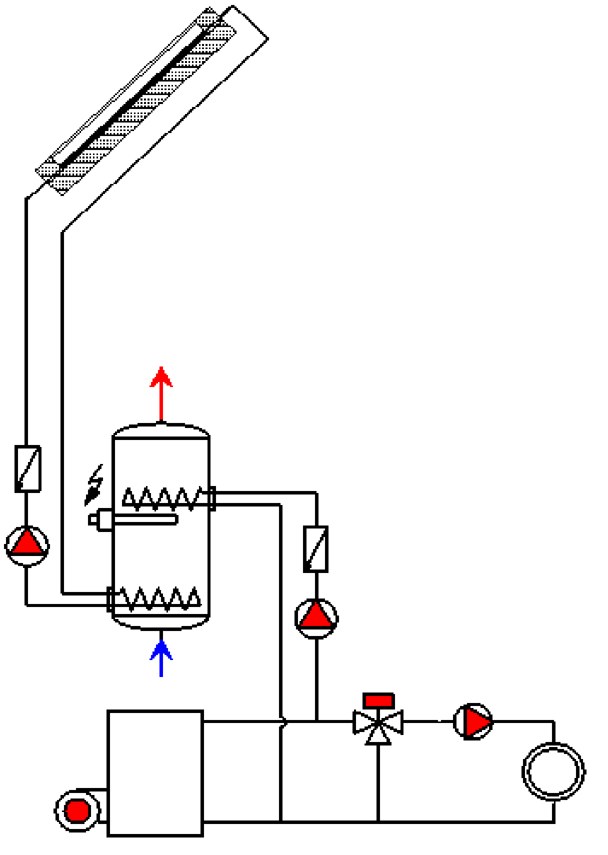
Solar systems

- solar system layouts
- heat demand
- collector area calculation

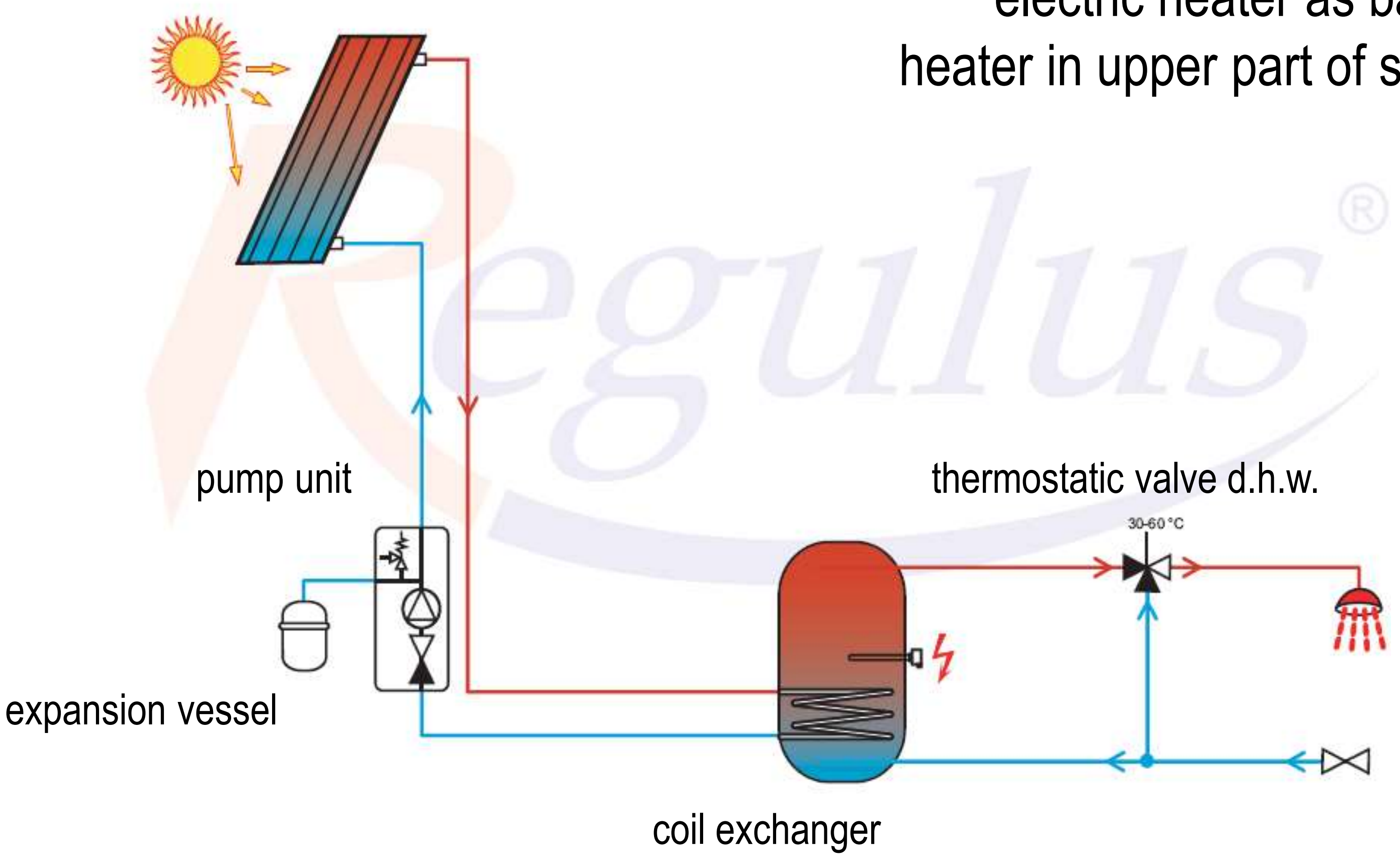


Solar systems - applications

- swimming pools (up to 35 °C)
- hot water systems (up to 70 °C)
- combined systems for hot water and space heating (up to 80 °C)
- district heating
- solar cooling and air-conditioning (up to 150 °C)
- industrial applications, process heat (up to 250 °C)
- solar thermal power plants (300 to 600 °C)
- air heating systems (drying, ventilation)

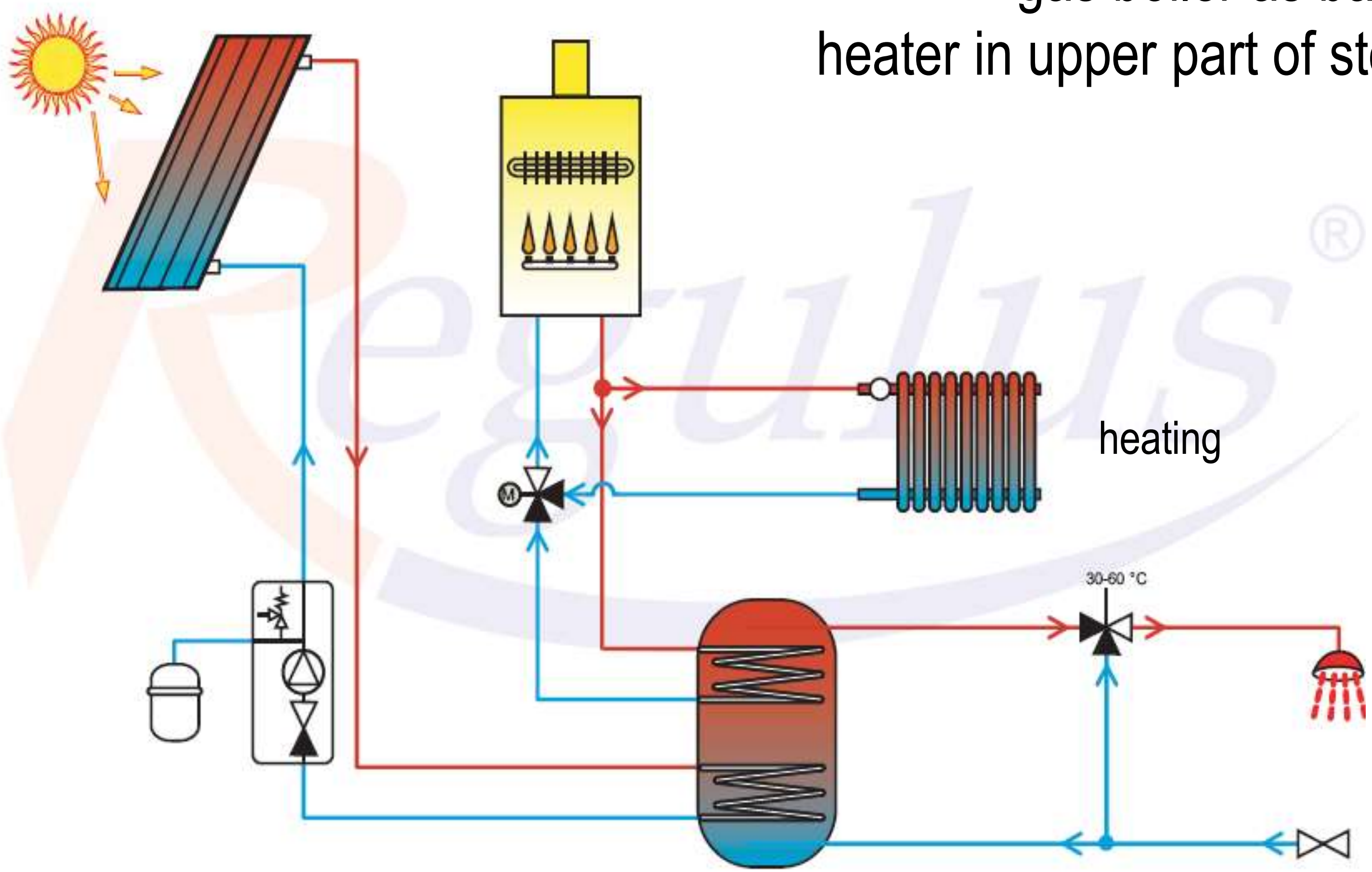
Solar hot water system with el. heater

electric heater as back-up
heater in upper part of storage



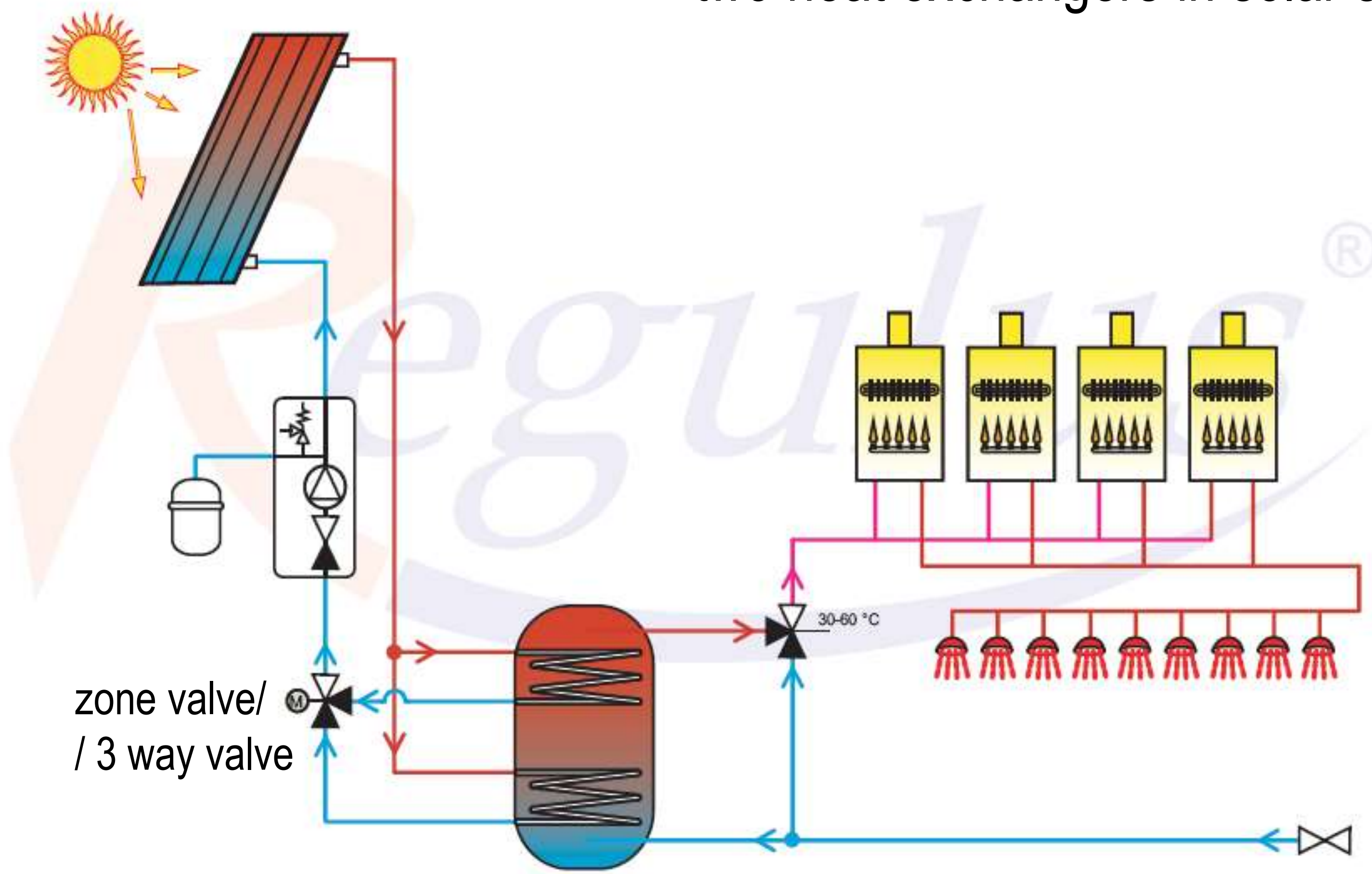
Solar hot water system with gas boiler

gas boiler as back-up
heater in upper part of storage

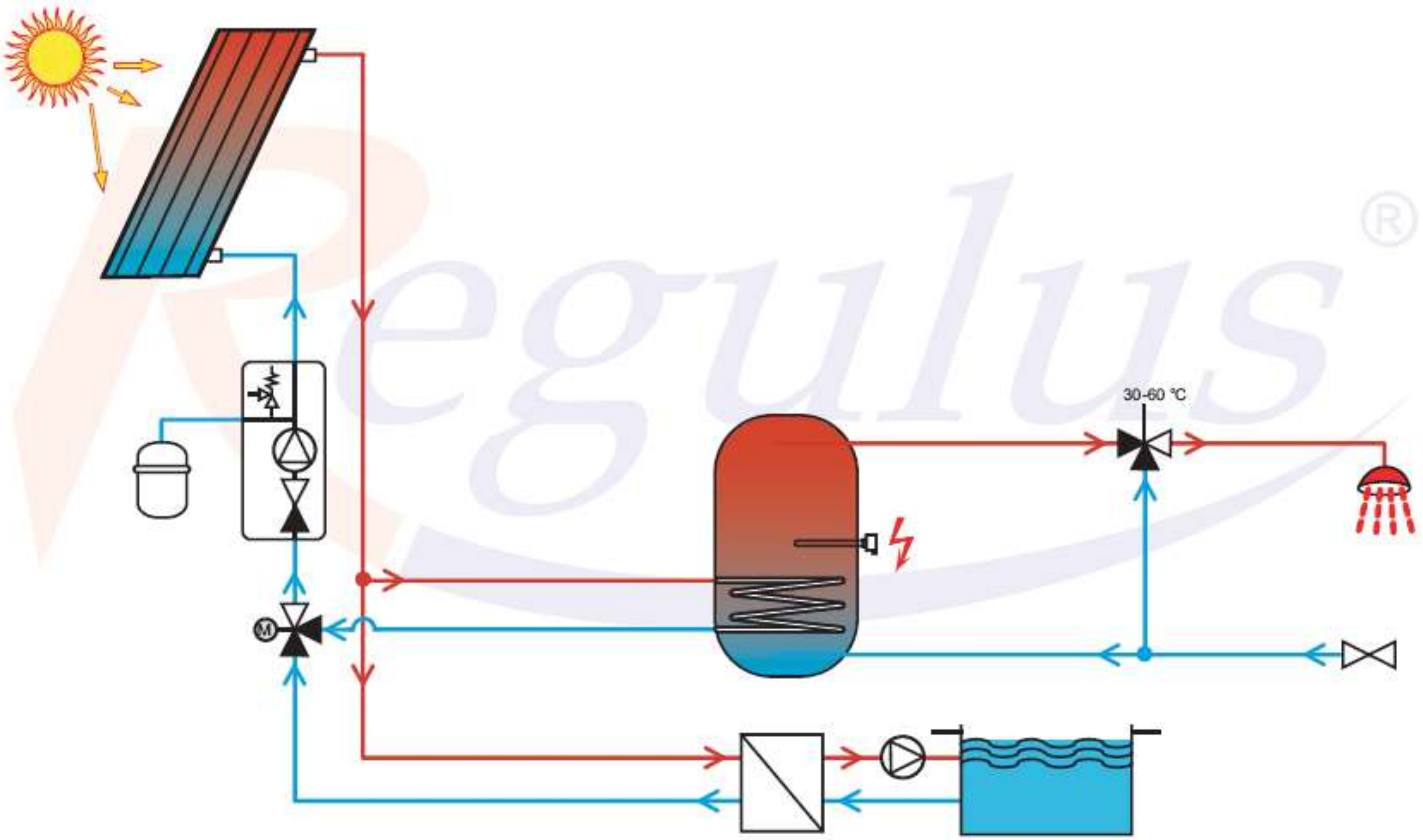


Solar hot water preheating system

two heat exchangers in solar storage

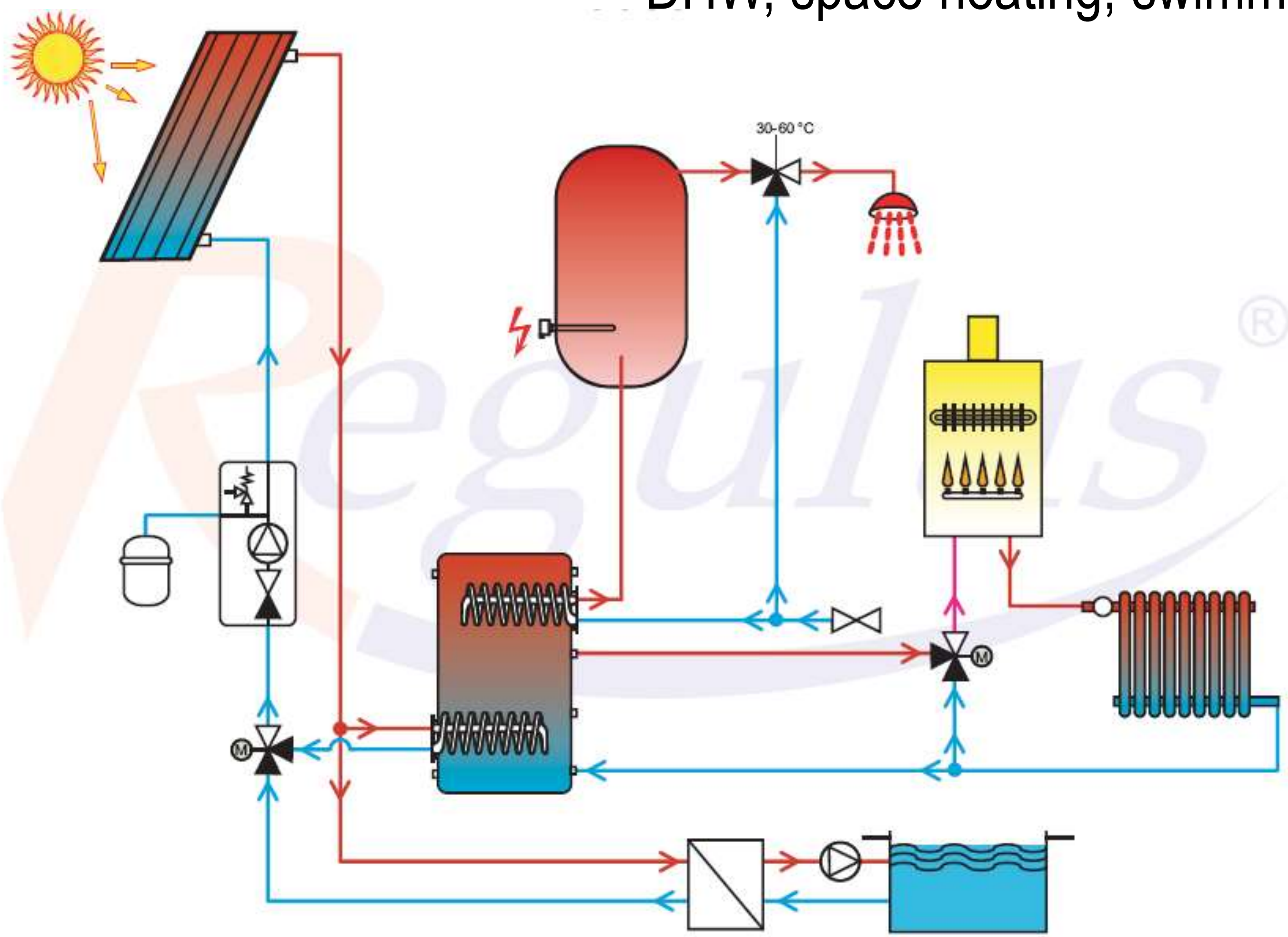


Solar hot water and swimming pool system

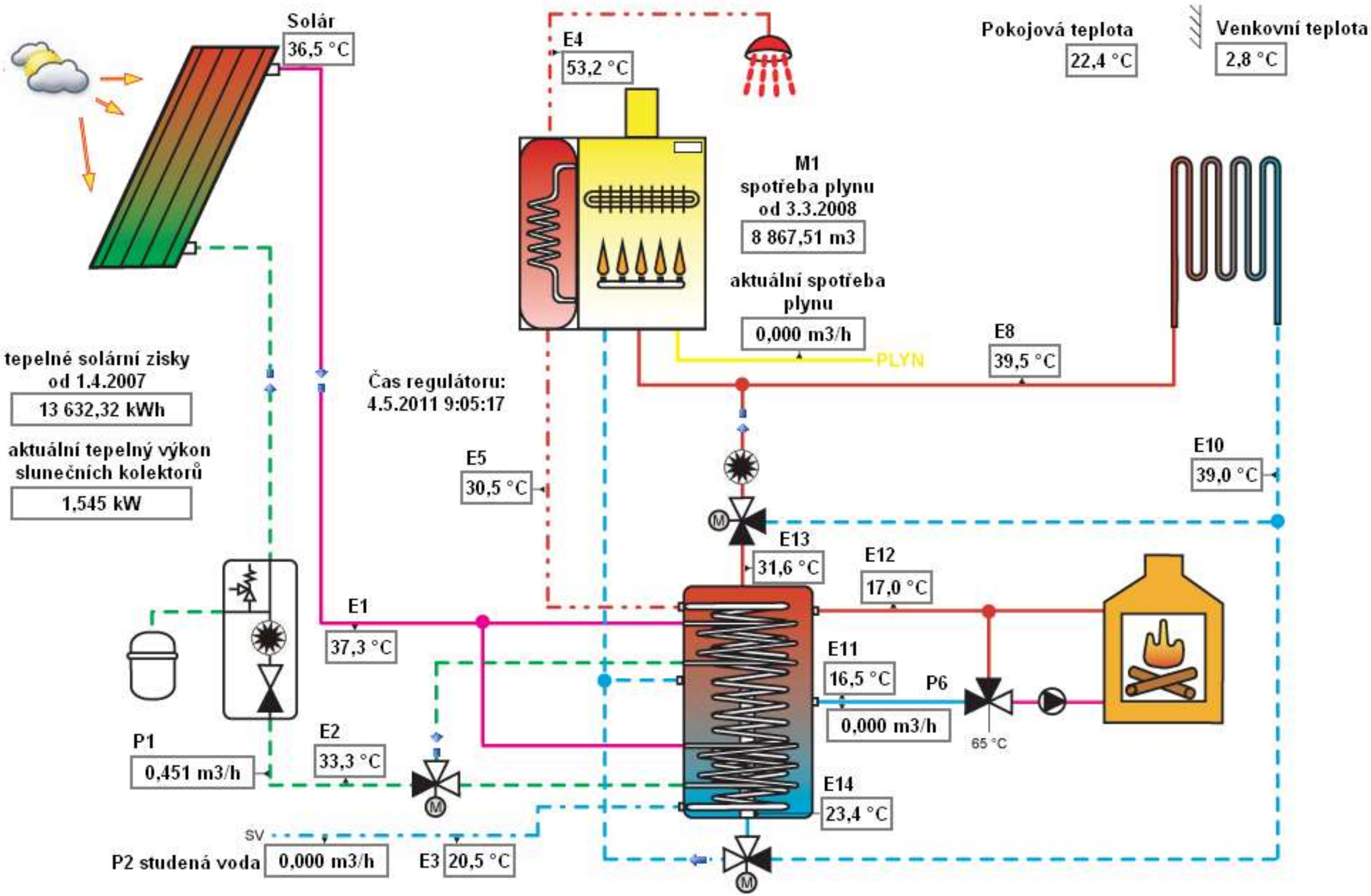


Solar multisource (multivalent) system

DHW, space heating, swimming pool



Solar multivalent system



Calculations

- **design of collector area**
  - daily heat demand in reference month
  - daily system yield for 1 m^2 of collector in reference month
  - determination of collector area
- **evaluation of annual yields**
  - monthly demands
  - monthly system energy yields for given collector area
  - balance, usability of yields
  - real energy yields

Solar systems design

- **heat demand reduction –** do the saving measures first !
- **hot water**
  - saving taps, insulation of hot water distribution system (pipes), control of water circulation by time, temperature
- **space heating**
  - low energy houses, passive houses (insulation, windows, ventilation heat recovery)
  - low temperature space heating systems

Solar systems design

- analyse the REAL heat demand (!)

- **hot water**
  - long-term measurement, short-term measurements, hot water loads at required temperatures
  - reference figures: usual HW demand **40 l/person.day** (60 °C)

- **space heating**
  - EN ISO 13 790 – simple but detailed calculation
  - degree-day method – simple but sufficient for solar system design or evaluation

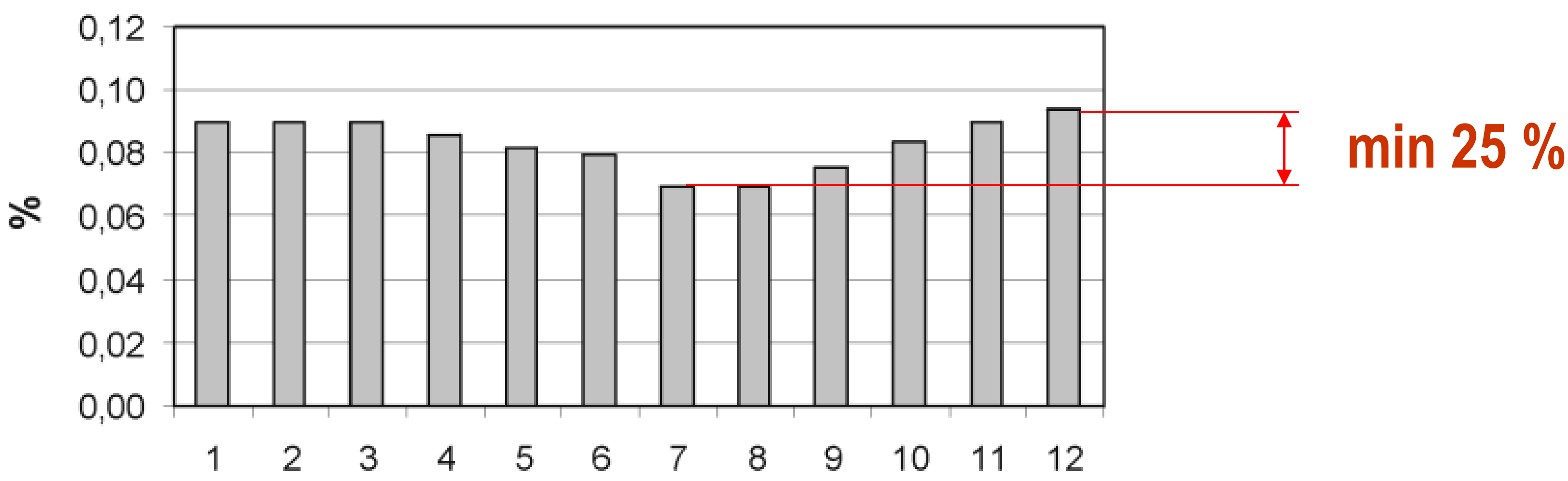
Daily hot water demand

residential (60 / 15 °C)	
low standard	10 to 20 l/person.day
usual standard	20 to 40 l/person.day
high standard	40 to 80 l/person.day

further data can be found e.g. in EN 15316-3-1, VDI 2067-4

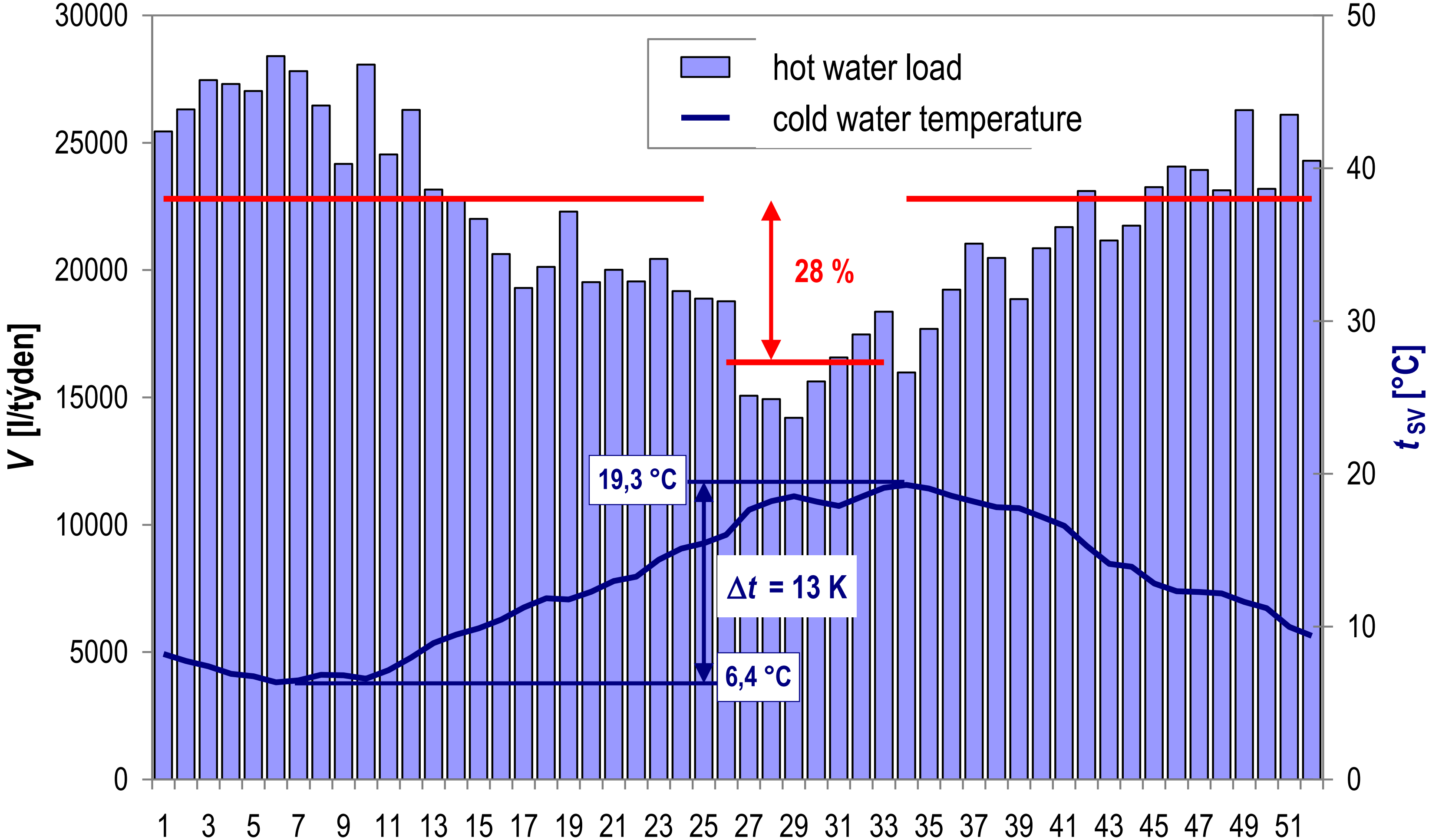
Annual profile of hot water load

- **summer decrease (residential sector)**
  - vacations
  - higher cold water temperature
  - user behaviour (summer shower, winter bath)



Measurement in block of flats

35 l/(per.day)



Daily hot water heat demand

$$Q_{HW} = \frac{V_{HW,day} \cdot \rho \cdot c \cdot (t_{HW} - t_{CW})}{3{,}6 \times 10^6}$$ **kWh/day**

$V_{HW,day}$	average daily hot water demand	[m^3/day]
ρ	water density	998 kg/m^3
c	specific heat of water	4187 J/kg.K
t_{CW}	cold water temperature	15 °C
t_{HW}	hot water temperature	60 °C

Heat loss of hot water preparation

$$Q_{p,HW} = Q_{HW} + Q_{loss,HW} = (1 + z) \cdot Q_{HW}$$

Hot water preparation	***z***
Local flow heaters	0.00
Central storage heaters (no hot water circulation)	0.15
Central storage heaters with controlled circulation	0.30
Central storage heaters with circulation (no control)	1.00
District heating, large distribution systems	> 2.00

Example 1 – hot water demand

- **daily demand**
  - 4 person x 40 l/person.day = **160 l/day**
  - hot water **60 °C**, cold water **15 °C**
  - preparation in hot water tank with volume 200 l
  - specific heat loss ***UA* = 1.3 W/K** (parameter of storage tank)
- **calculate**
  - total hot water preparation demand

Example 1

$$Q_{HW} = \frac{V_{HW,day} \cdot \rho \cdot c \cdot (t_{HW} - t_{CW})}{3{,}6 \times 10^6}$$

$$Q_{HW} = \frac{0.16 \cdot 1000 \cdot 4187 \cdot (60 - 15)}{3{,}6 \times 10^6} =$$ **8.4 kWh/day**

$$Q_{loss,HW} = \frac{UA \cdot (t_{st} - t_{room}) \cdot 24}{1000}$$ **daily heat loss**

$$Q_{loss,HW} = \frac{1.3 \cdot (60 - 20) \cdot 24}{1000} =$$ **1.25 kWh/day**

Example 1

total heat demand for hot water

$$Q_{d,HW} = Q_{HW} + Q_{loss,HW} = \quad \mathbf{9.65\ kWh/day}$$

fraction of heat loss

$$z = \frac{Q_{loss,HW}}{Q_{HW}} = \frac{1.25}{8.4} = \quad \mathbf{0.15}$$

Space heating heat demand

- **EN ISO 13790** – Energy performance of buildings – Calculation of energy demand for heating and cooling
  - **monthly balance**
  - heat losses (transmission, ventilation)
  - solar heat gains
  - internal heat gains
  - usability of gains based on accumulation in internal construction (time constant calculation)

Space heating heat demand

- **degree-day method –** simplified approach (daily, monthly, seasonal)

$$Q_{SH} = 24 \cdot \varepsilon \cdot \dot{Q}_N \cdot \frac{\left(t_{i,avg} - t_{e,avg}\right)}{\left(t_{i,N} - t_{e,N}\right)}$$ **kWh/day**

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

Space heating heat demand

- **correction factor for degree day method**

(reduction in the consumption of heat) Include:
- effects of regulation - discontinuous heating - solar heat gains - internal heat gains

Building energy performance	ε
usual standard legislation requirement	0.75
low-energy standard advanced constructions, ventilation with heat recovery	0.60
passive standard passive house constructions, ventilation with efficient heat recovery	0.50

Example 2 – space heating demand

- **design parameters**
  - building design heat loss 5 kW
  - design outdoor temperature $t_{e,N}$ = -12 °C
  - design indoor temperature $t_{i,N}$ = 20 °C
- **calculate**
  - daily space heating demand for April
  - $t_{i,avg}$ = 20 °C
  - $t_{e,avg}$ = 8,8 °C
  - correction factor ε = 0.6

Example 2 – daily heat demand

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

$$Q_{SH} = 24 \cdot 0.6 \cdot 5 \cdot \frac{\left(20 - 8.8\right)}{\left(20 - (-12)\right)} =$$ **25.2 kWh/day (for April)**

Example 2 – heating season demand

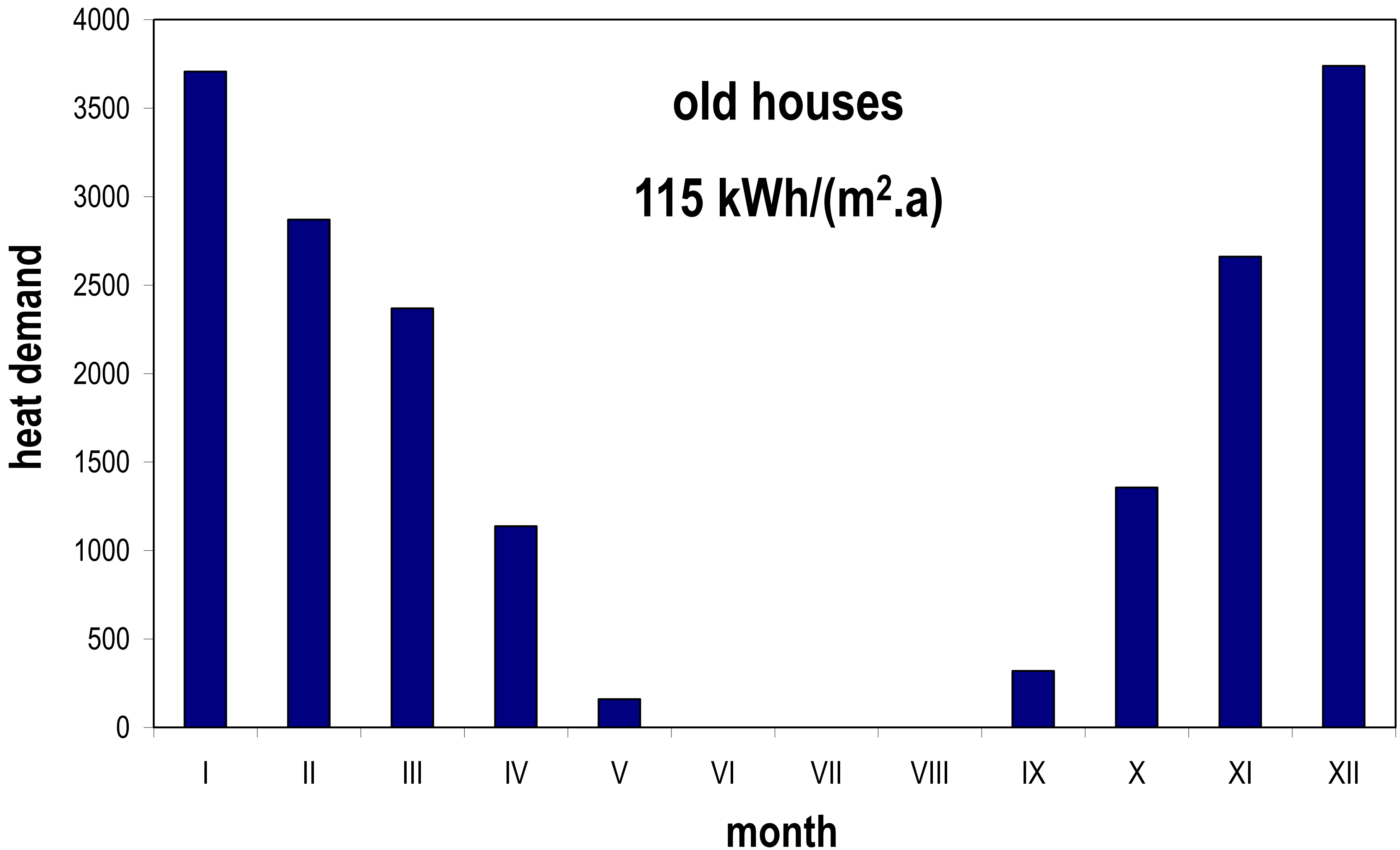
$$Q_{SH} = 24 \cdot \varepsilon \cdot \dot{Q}_N \cdot \frac{\left(t_{i,avg} - t_{e,avg}\right)}{\left(t_{i,N} - t_{e,N}\right)} \cdot d$$

number of days in heating season: ***d* = 225 days**

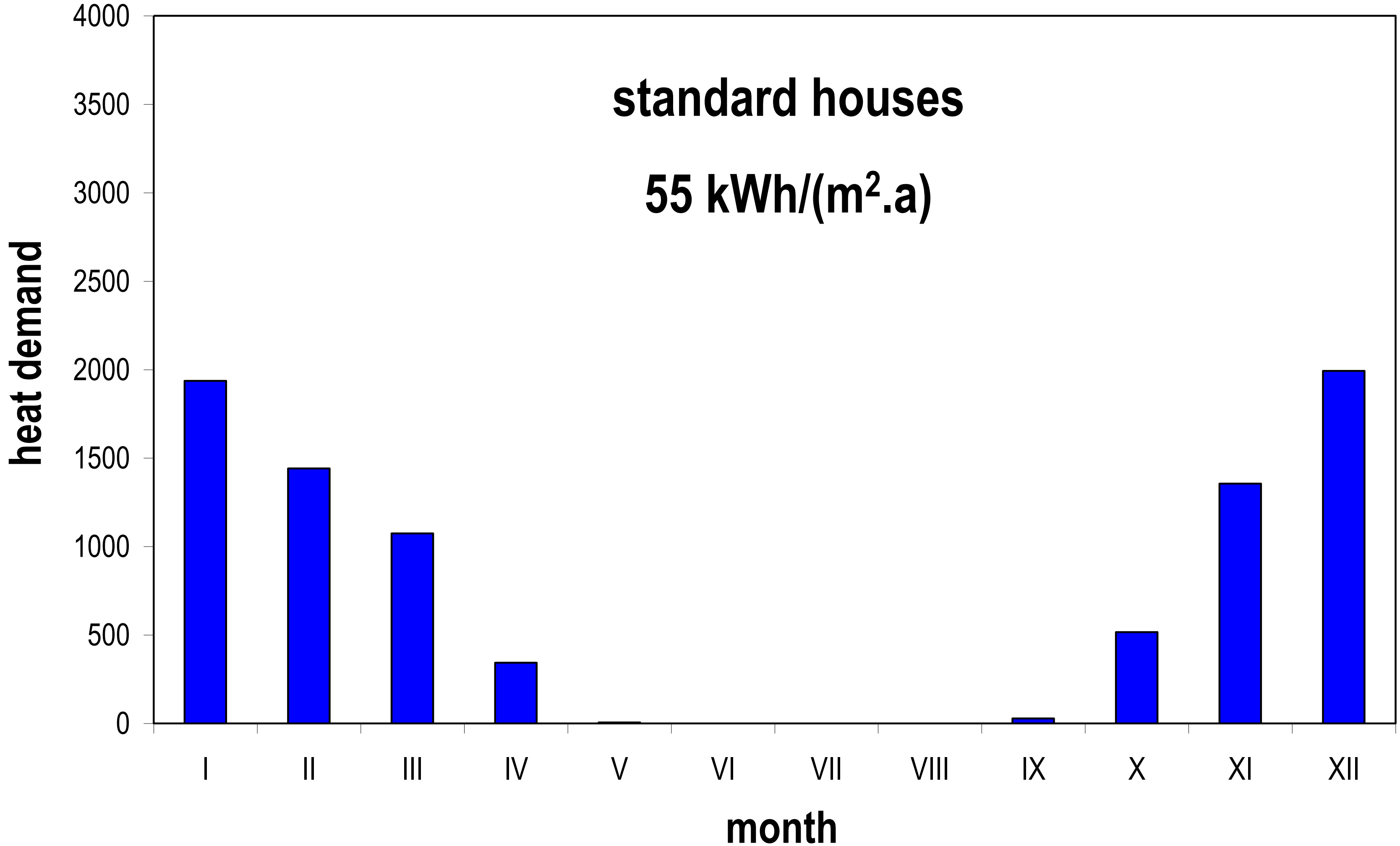
average temperature: **$t_{e,avg}$ = 4.3 °C**

$$Q_{SH} = 24 \cdot 0.6 \cdot 5 \cdot \frac{(20 - 4.3)}{(20 - (-12))} \cdot 225 =$$ **7948 kWh/season**

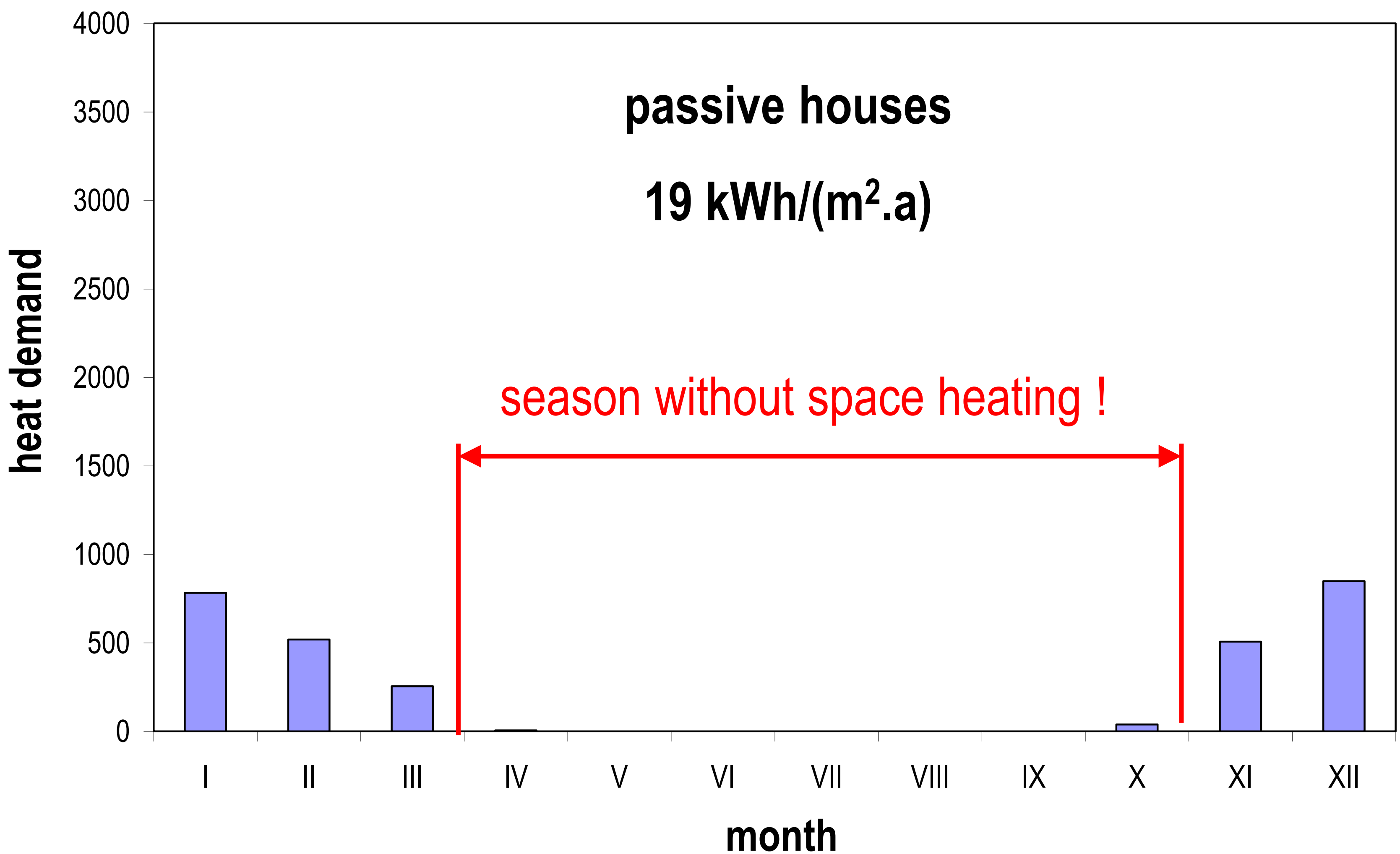
Space heating heat demand



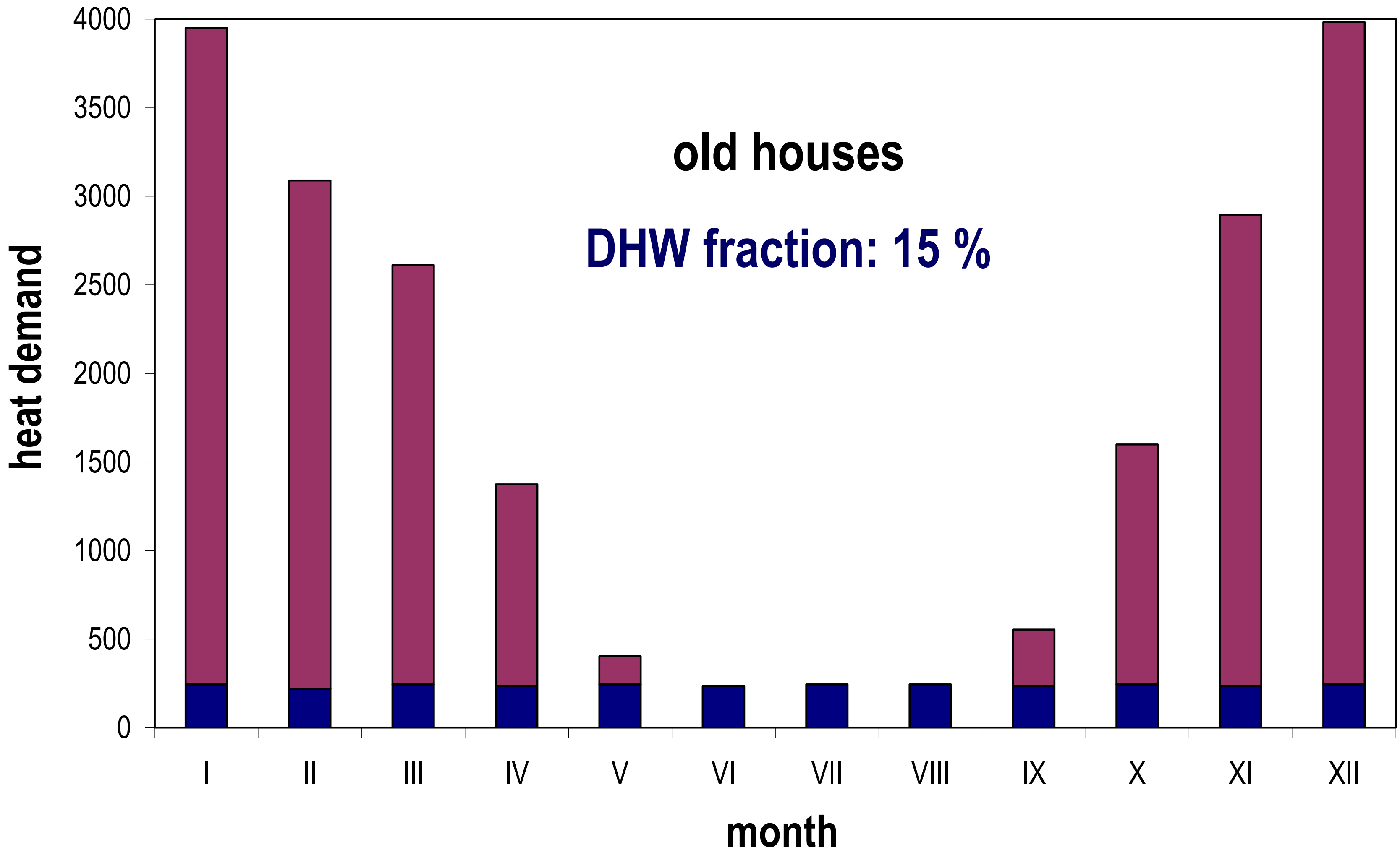
Space heating heat demand



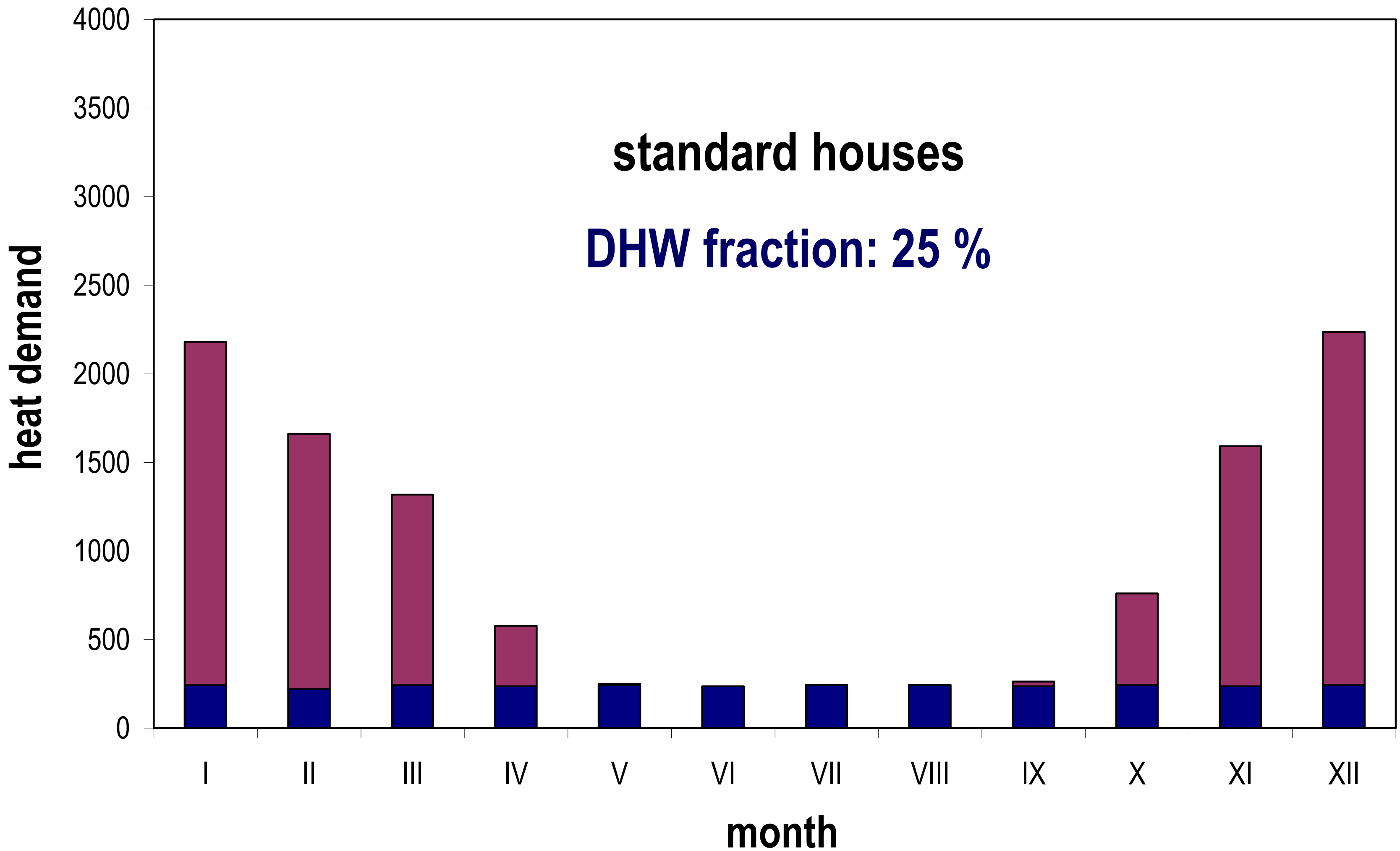
Space heating heat demand



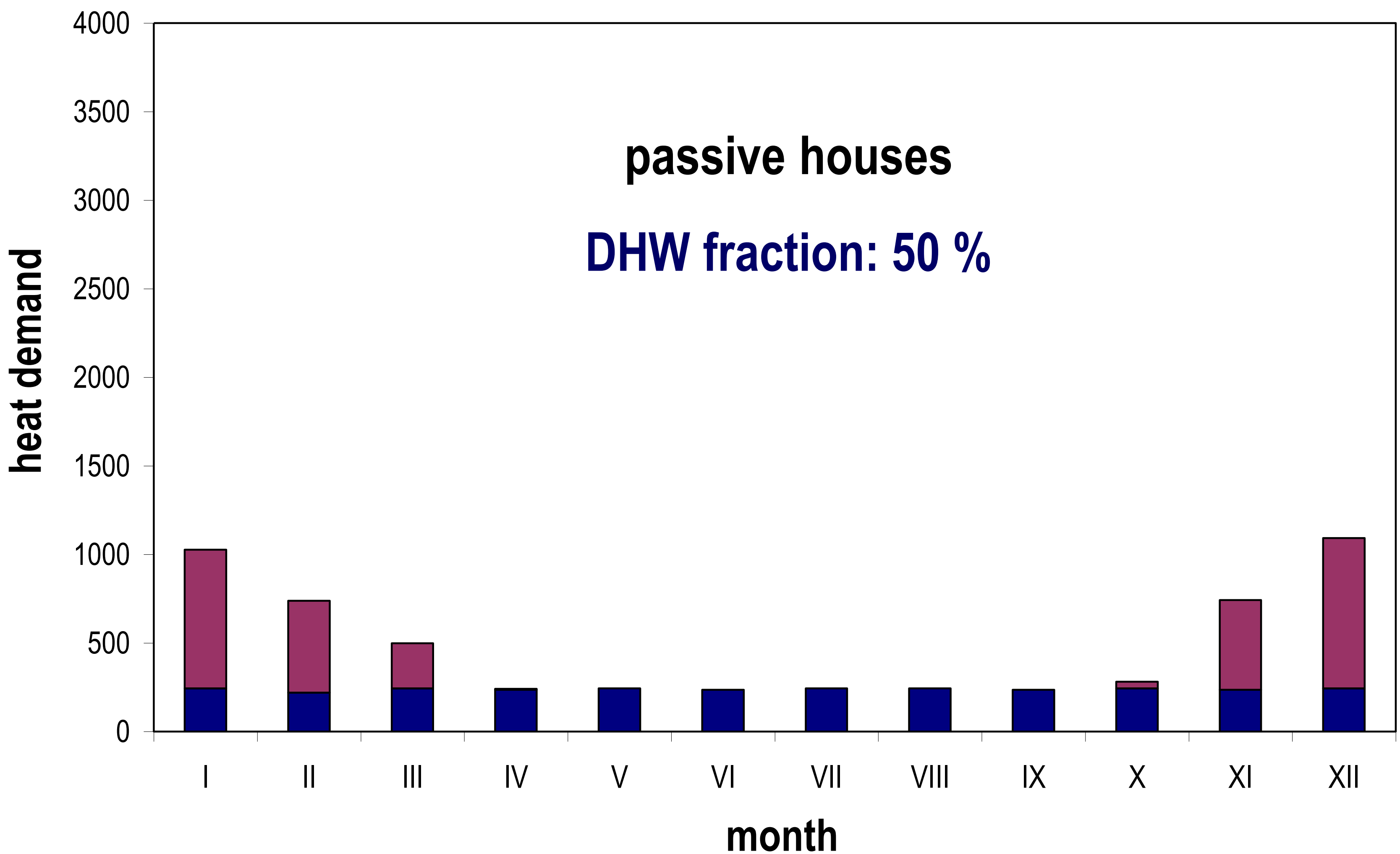
Total heat demand



Total heat demand



Total heat demand



Usable heat gain of collector

- usable heat gain $Q_{k,u}$ [kWh/m²] of solar collectors in given period (day, month)

$$Q_{k,u} = 0{,}9 \cdot \eta_k \cdot H_{T,day} \cdot A_k \cdot (1 - p) \qquad \text{kWh/day}$$

  - efficiency of solar collector for given conditions η_k
  - solar irradiation of given plane of solar collector $H_{T,day}$
    - *climate data from tables*
  - heat loss of solar system
    - reduction factors p
    - *according to type and size of the solar system, data from tables*

Solar collector efficiency

- average daily collector efficiency η_k

$$\eta_k = \eta_0 - a_1 \cdot \frac{t_{k,m} - t_{e,s}}{G_{T,m}} - a_2 \cdot \frac{\left(t_{k,m} - t_{e,s}\right)^2}{G_{T,m}}$$

- mean fluid temperature $t_{k,m}$ in collector during the day
  - *according to type and size of solar system*
- for mean ambient temperature in time of sunshine $t_{e,s}$
  - *climate data from tables*
- mean daily solar irradiance $G_{T,m}$ for given plane (slope, orientation)
  - *climate data from tables*

Solar collector efficiency

- mean daily fluid temperature in collector $t_{k,m}$

Application	$t_{k,m}$ [°C]
Water preheating, solar fraction < 35 %	35
Hot water preparation, 35 % < solar fraction < 70 %	40
Hot water preparation, solar fraction > 70 %	50
Hot water and space heating, solar fraction < 25 %	50
Hot water and space heating, solar fraction > 25 %	60

Heat losses – relative figures

- **reduction factor**

$$Q_{k,u} = 0{,}9 \cdot \eta_k \cdot H_{T,day} \cdot A_k \cdot (1 - p)$$

Application	***p***
Hot water preparation, up to 10 m^2	0,20
Hot water preparation, from 10 to 50 m^2	0,10
Hot water preparation, from 50 to 200 m^2	0,05
Hot water preparation, above 200 m^2	0,03
Hot water and space heating, up to 10 m^2	0,30
Hot water and space heating, from 10 to 50 m^2	0,20
Hot water and space heating, from 50 to 200 m^2	0,10
Hot water and space heating, above 200 m^2	0,06

Determination of required collector area

Collector area design A_k

- for given **design day** in **typical** design month
  - climate and operation conditions
- to provide coverage of considered heat demand
  - according to application, local conditions

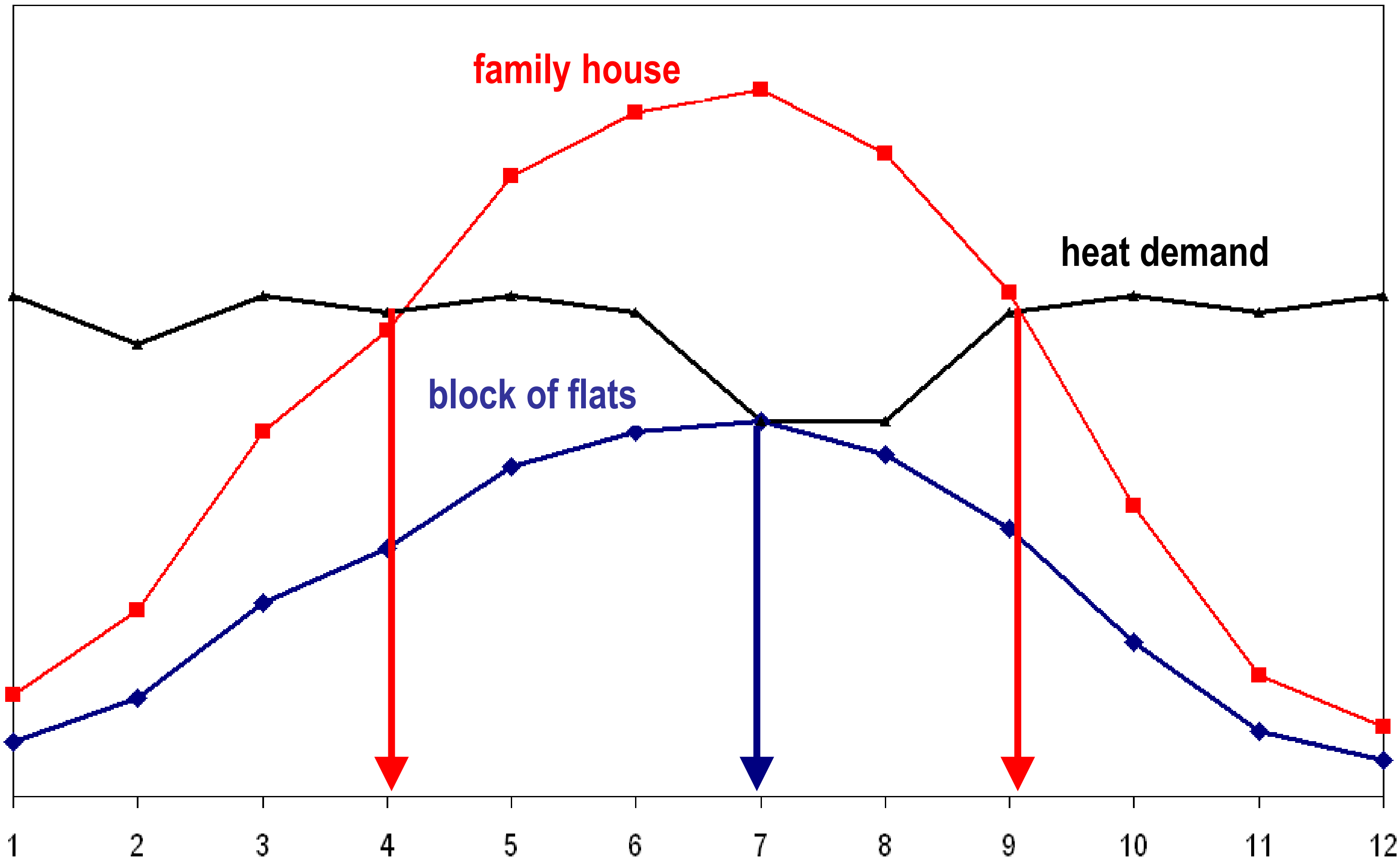
$$Q_{k,u} = 0{,}9 \cdot \eta_k \cdot H_{T,day} \cdot A_k \cdot (1 - p) = Q_p$$

Design months: hot water

- **family houses**
  - **April** and **September** (100% design fraction = meet a needs in April)
  - mean fluid temperature $t_{k,m}$ **= 40 °C**
  - coverage of **60** % annual hot water heat demand

- **block of flats**
  - **July** (100% design fraction)
  - mean fluid temperature $t_{k,m}$ **= 40 °C**
  - coverage of **40 - 50** % annual hot water heat demand

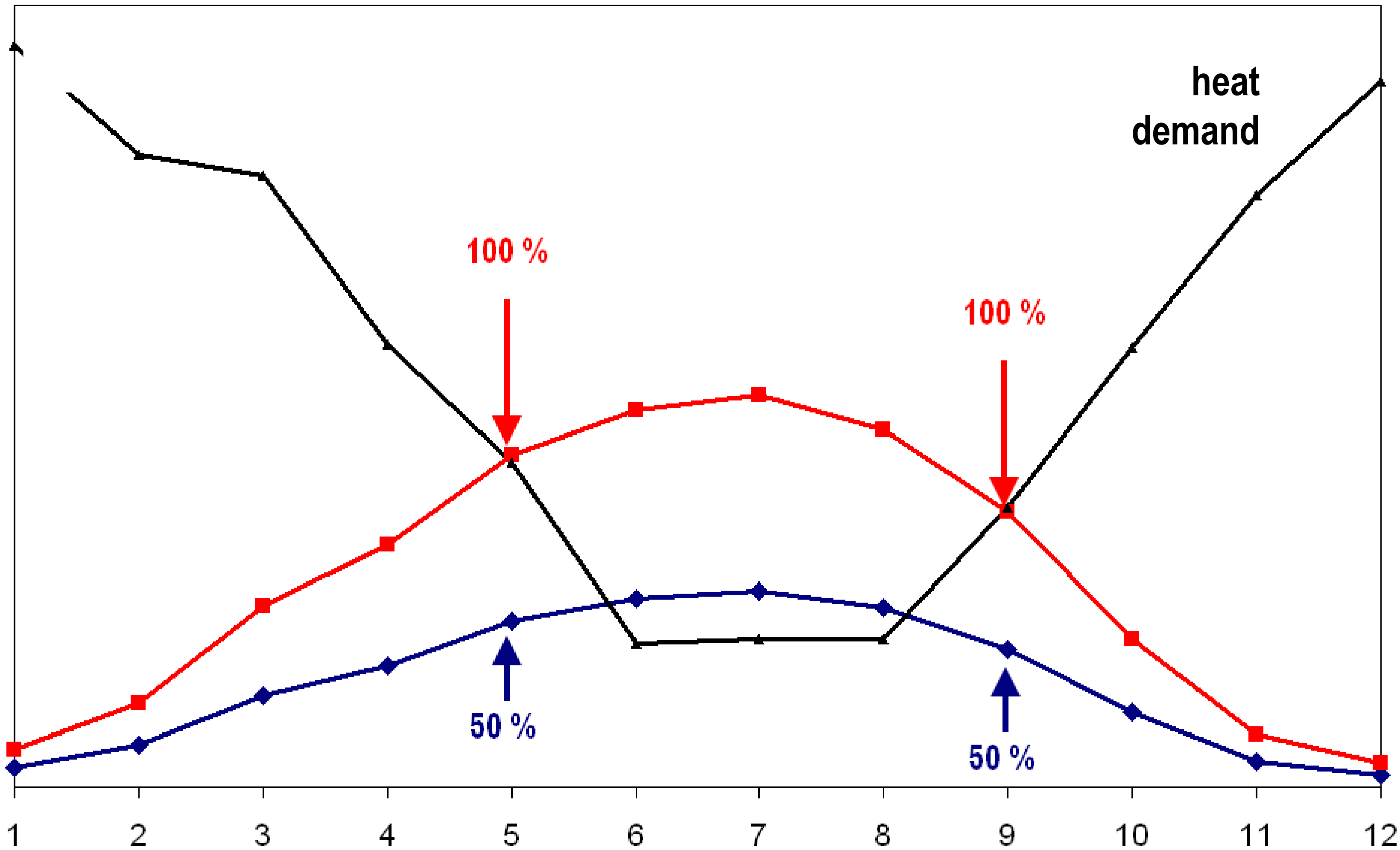
Design months: hot water



Combined HW and SH systems

- **hot water and space heating**
  - **May** and **September**
  - mean fluid temperature $t_{k,m}$ **= 50 °C**
  - consider meaningful use of summer excess heat gains
  - consider solar fraction in spring and autumn (100 % ?)

Combined systems



Influence on components design

- **flowrate in solar system**
  - pipe dimensions
  - insulation thickness
- **hydraulic losses, hydraulic concept**
  - system circulation pump
- **volume of solar system**
  - size of expansion vessel
- **supporting structure**
- **heat exchanger size, safety valve**

collector area influences the size of other system components

Example 3 – solar DHW for family house

Example 3 – solar DHW system

- **daily demand**
  - 4 person x 35 l/person.day = **140 l/day**
  - hot water **60 °C**, cold water **15 °C**
  - hot water tank, ***z* = 0.15**
  - small system up to 10 m^2, ***p* = 0.20**
- **calculate**
  - total heat demand for hot water preparation
  - determine **solar collector area** for solar DHW preparation system

Example 3 – heat demand

$$Q_{d,HW} = \frac{(1+z)\cdot V_{HW,day}\cdot \rho \cdot c \cdot (t_{HW} - t_{CW})}{3{,}6 \times 10^6}$$

$$Q_{d,HW} = \frac{(1+0.15)\cdot 0.14 \cdot 1000 \cdot 4187 \cdot (60-15)}{3{,}6 \times 10^6} = \quad \mathbf{8.4\ kWh/day}$$

Example 3 – solar collector

- **solar collector: flat-plate**
  - η_0 = 0.78
  - a_1 = 3.5 W/m^{2}K
  - a_2 = 0.015 W/m^{2}K^2
  - A_{k1} = 2.0 m^2 (aperture)

Example 3 – balance

- design for family house = design for April (September)
- **daily balance**

$$Q_{k,u} = 0{,}9 \cdot \eta_k \cdot H_{T,day} \cdot A_k \cdot (1 - p) = Q_{d,HW}$$

$$0{,}9 \cdot \eta_k \cdot H_{T,day} \cdot A_k \cdot (1 - 0.2) = Q_{d,HW}$$

Example 3 – solar irradiation

- daily total solar irradiation for April (September), Prague
- slope 45°, south
- theoretical $H_{\mathrm{T,day,th}}$ = **7.16 (6.42) kWh/m^2.day**
- diffuse $H_{\mathrm{T,day,dif}}$ = **1.34 (1.16) kWh/m^2.day**
- relative period of sunshine τ_{r} = **0.45 (0.53)**

$$H_{\mathrm{T,day}} = H_{\mathrm{T,day,th}} \cdot \tau_{\mathrm{r}} + H_{\mathrm{T,day,dif}} \left(1 - \tau_r\right) =$$ **3.96 (3.95) kWh/m^2.day**

Example 3 – collector efficiency

- average daily solar collector efficiency
- fluid temperature **$t_{k,m}$ = 40 °C**
- ambient temperature in period of sunshine $t_{e,s}$ = **12.1 (19.4) °C**
- mean daily irradiance $G_{T,m}$ = **527 (516) W/m²**

$$\eta_k = \eta_0 - a_1 \cdot \frac{t_{k,m} - t_{e,s}}{G_{T,m}} - a_2 \cdot \frac{\left(t_{k,m} - t_{e,s}\right)^2}{G_{T,m}} = \mathbf{0.57\ (0.63)}$$

Example 4 – collector area

- **required solar collector area**

$$A_k = \frac{Q_{d,HW}}{0{,}9 \cdot \eta_k \cdot H_{T,day} \cdot (1-p)}$$

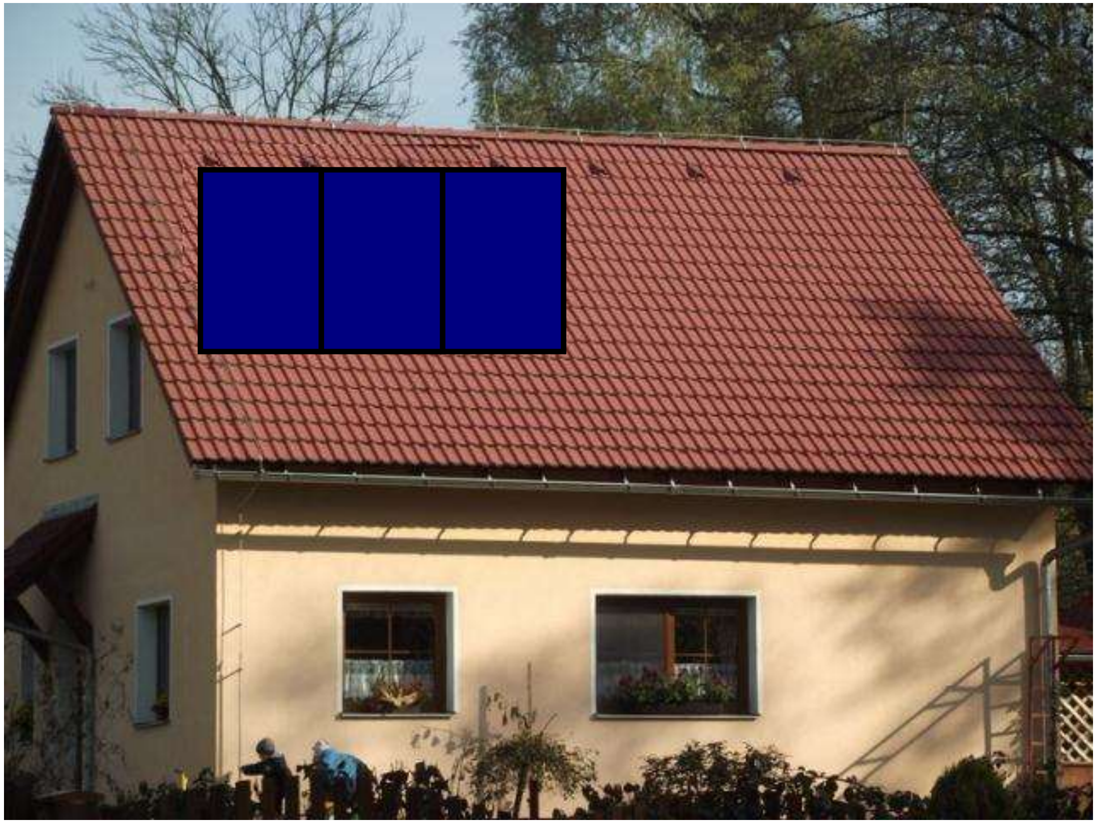
$$A_k = \frac{8.4}{0.9 \cdot 0.57 \cdot 3.96 \cdot (1-0.2)} = \quad \mathbf{5.2\ m^2}$$

4.9 m²

$$A_k = \frac{8.4}{0.9 \cdot 0.63 \cdot 3.95 \cdot (1-0.2)} = \quad \mathbf{(4.7\ m^2)}$$

number of collectors = ?   2 pcs (=4 m²) or 3 pcs (=6 m²)?

Example 3 – solar DHW for family house



next lecture !

Example 4 – solar combisystem

- **hot water daily demand** (same as previous example)
  - 4 person x 35 l/person.day = **140 l/day**
  - hot water **60 °C**, cold water **15 °C**
  - heat loss factor ***z* = 15 %**
- **space heating**
  - nominal heat loss 4 kW (design indoor 20 °C, design outdoor -12 °C)
  - share of heating system losses ***v* = 5 %**

Daily heat demand for hot water

$$Q_{d,HW} = \frac{(1+z)\cdot V_{HW,day}\cdot \rho \cdot c \cdot (t_{HW} - t_{CW})}{3{,}6\times 10^{6}}$$

$$Q_{d,HW} = \frac{(1+0.15)\cdot 0.14 \cdot 1000 \cdot 4187 \cdot (60-15)}{3{,}6\times 10^{6}} = \text{8.4 kWh/day}$$

Daily heat demand for space heating

May: $t_{e,avg} = 13.6\ °C$ $\varepsilon = 0.6$

September: $t_{e,avg} = 14.9\ °C$ $t_i = 20\ °C$

$$Q_{d,SH} = 24 \cdot \varepsilon \cdot \dot{Q}_N \cdot \frac{\left(t_{i,avg} - t_{e,avg}\right)}{\left(t_{i,N} - t_{e,N}\right)}\left(1 + v\right)$$

$$Q_{d,SH} = 24 \cdot 0.6 \cdot 4 \cdot \frac{\left(20 - 13.6\right)}{\left(20 - \left(-12\right)\right)}\left(1 + 0.05\right) =$$ **12.1 kWh/day**

$$Q_{d,SH} = 24 \cdot 0.6 \cdot 4 \cdot \frac{\left(20 - 14.9\right)}{\left(20 - \left(-12\right)\right)}\left(1 + 0.05\right) =$$ **9.6 kWh/day**

Total heat demand

May

$$Q_{d,HW+SH} = Q_{d,HW} + Q_{d,SH} = 8.4 + 12.1 = \textbf{20.5 kWh/day}$$

September

$$Q_{d,HW+SH} = Q_{d,HW} + Q_{d,SH} = 8.4 + 9.6 = \textbf{18.1 kWh/day}$$

Example 4 – solar collector

- **solar collector: flat-plate**
  - $\eta_0 = 0.78$
  - $a_1 = 3.5\ \mathrm{W/m^2K}$
  - $a_2 = 0.015\ \mathrm{W/m^2K^2}$
  - $A_{k1} = 2.0\ \mathrm{m^2}$ (aperture)

Example 4 – solar irradiation

- daily total solar irradiation for May (September), Prague
- slope 45°, south
- theoretical $H_{\mathrm{T,day,th}}$ = **7.94 (6.42) kWh/m².day**
- diffuse $H_{\mathrm{T,day,dif}}$ = **1.62 (1.16) kWh/m².day**
- relative period of sunshine τ_{r} = **0.51 (0.53)**

$$H_{\mathrm{T,day}} = H_{\mathrm{T,day,th}} \cdot \tau_{\mathrm{r}} + H_{\mathrm{T,day,dif}} \left(1 - \tau_r\right) = $$ **4.84 (3.95) kWh/m².day**

Example 4 – collector efficiency

- average daily solar collector efficiency
- fluid temperature **$t_{k,m}$ = 50 °C**
- ambient temperature in period of sunshine $t_{e,s}$ = **16.6 (19.4) °C**
- mean daily irradiance $G_{T,m}$ = **521 (516) W/m²**

$$\eta_k = \eta_0 - a_1 \cdot \frac{t_{k,m} - t_{e,s}}{G_{T,m}} - a_2 \cdot \frac{(t_{k,m} - t_{e,s})^2}{G_{T,m}} = \mathbf{0.52\ (0.55)}$$

Example 4 – collector area

- **required solar collector area**

$$A_k = \frac{Q_{d,HW+SH}}{0{,}9 \cdot \eta_k \cdot H_{T,day} \cdot (1-p)}$$

p = 0,30 (for A < 10 m^2)

p = 0,20 (for A > 10 m^2)

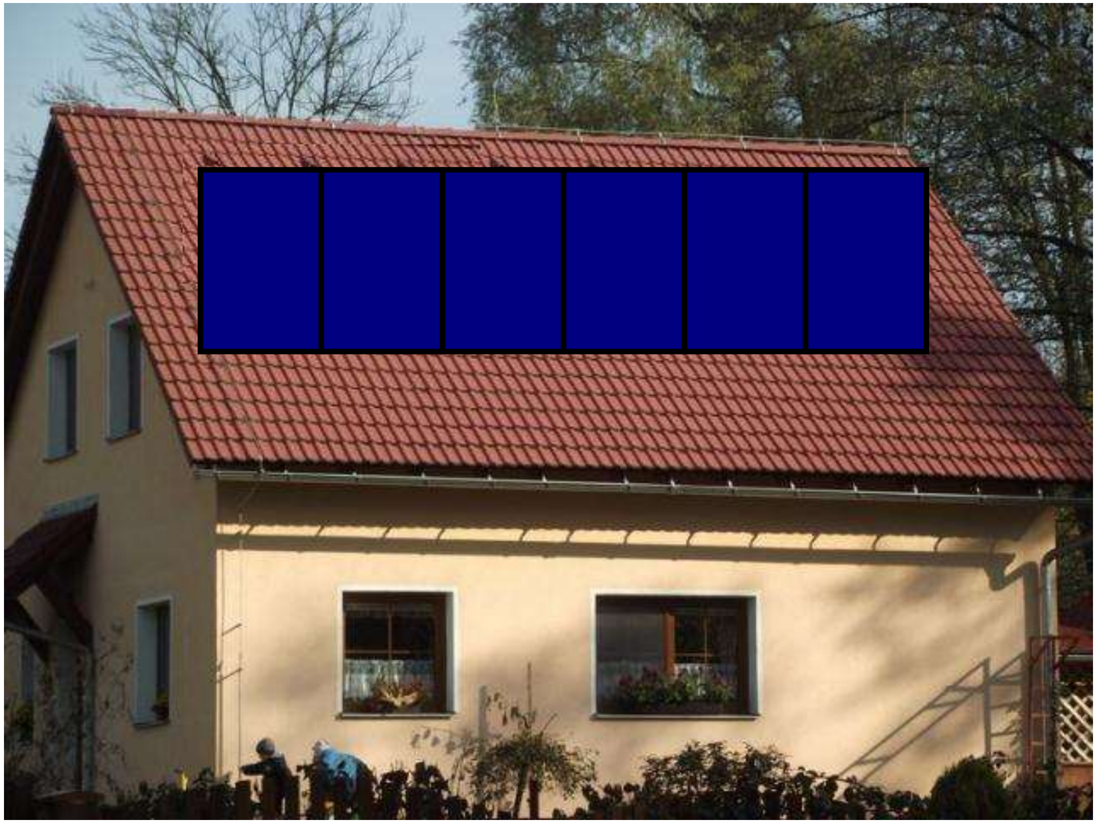
$$A_k = \frac{20.5}{0.9 \cdot 0.52 \cdot 4.84 \cdot (1-0.2)} =$$ **11.3 m^2**

11.5 m^2

$$A_k = \frac{18.1}{0.9 \cdot 0.55 \cdot 3.95 \cdot (1-0.2)} =$$ **11.6 m^2**

number of collectors = ? 5 pcs (=10 m^2) or 6 pcs (=12 m^2)?

Example 4 – solar combisystem



next lecture !

Next lecture – annual performance