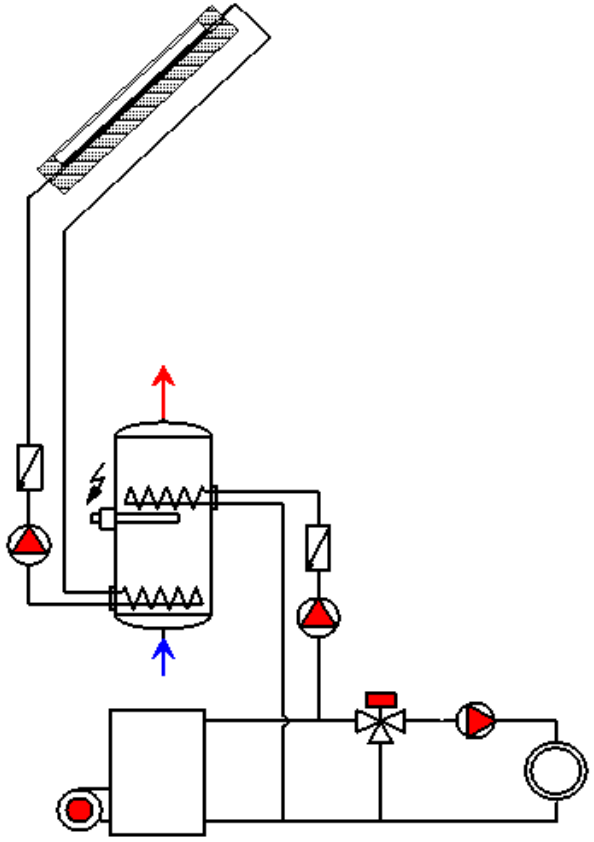
# Solar systems

- evaluation of performance
- annual yields of solar systems
- typical values



# Annual performance

**Annual solar energy yields / savings by solar system installation**

- simplified methods

  simple balance method (month)

  f-chart method

- simulation methods

  static – hour by hour calculation of main components

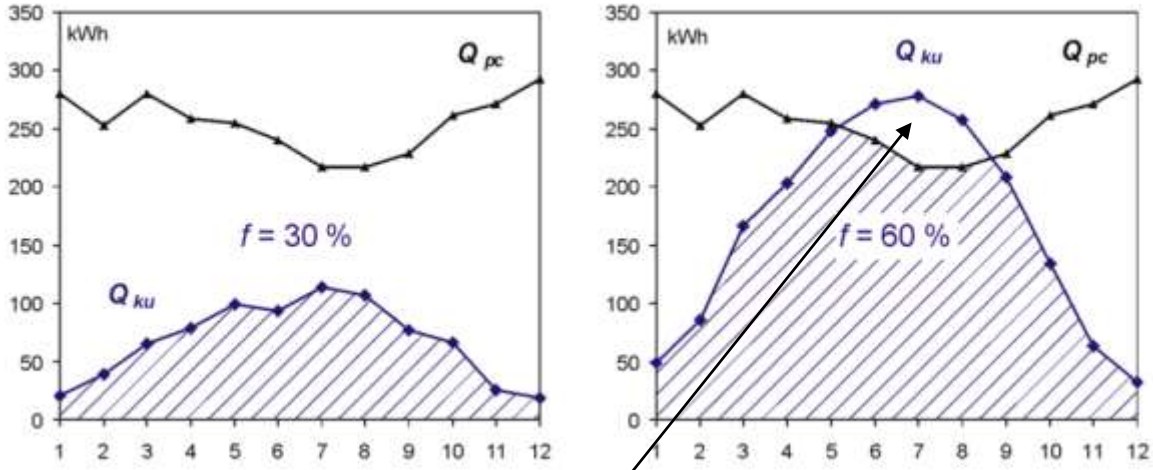
  dynamic simulation – for complex systems with high degree of detail

# Simple balance method

## Balance of solar system

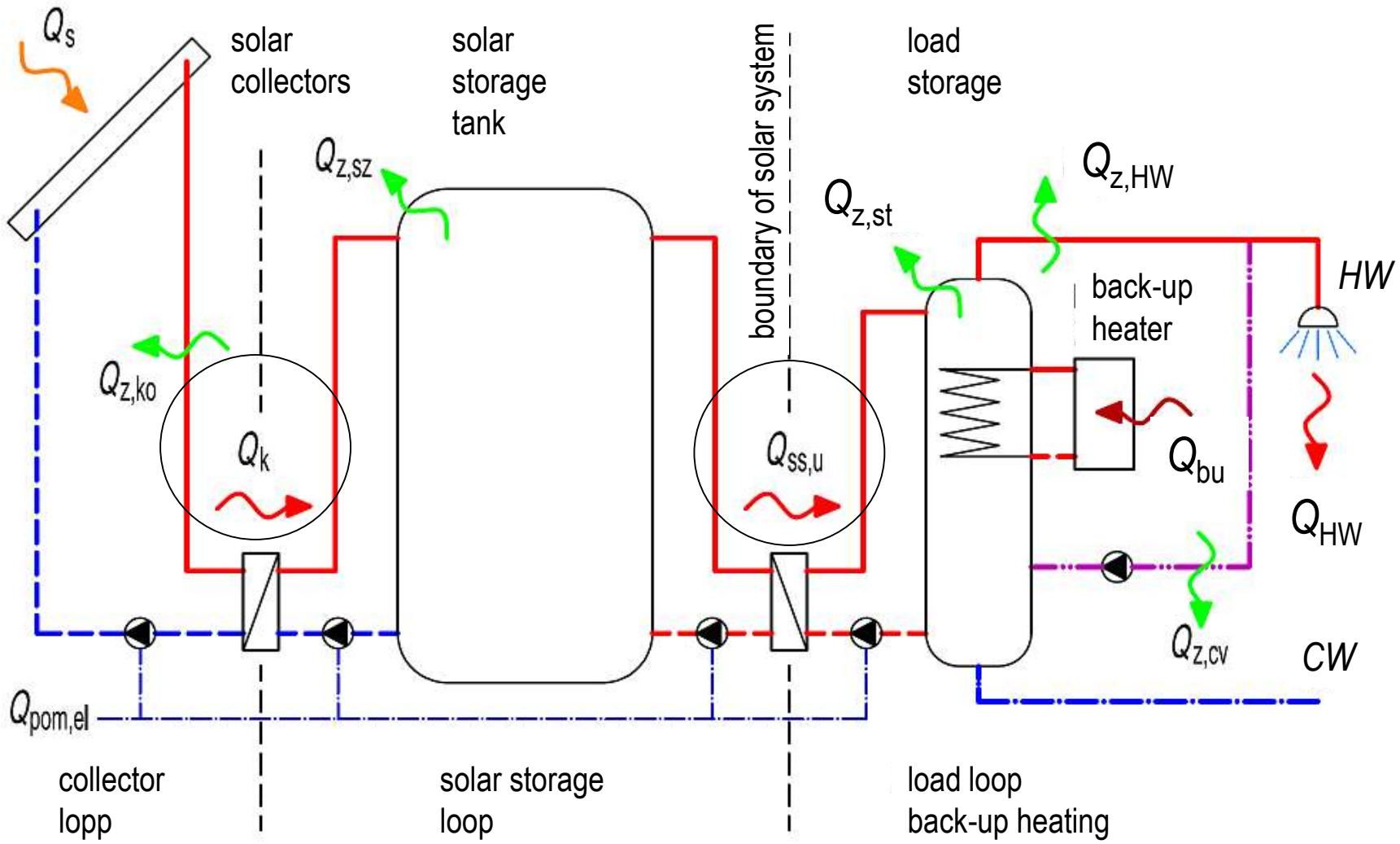
- for given collector area $A_k$
- for **all months** (reference design days, boundary conditions)

$$Q_{ss,u} = \min (Q_{k,u}; Q_d)$$




- usability of collector heat gains results from comparison with heat demand in individual months
- **excess heat gains can't be considered (!)**

# Balance of solar system




**supplied into storage $Q_k$** **supplied to load $Q_{ss,u}$**

# Solar system parameters

- **Annual heat gain, solar yield [kWh/a]**
  - supplied into storage $Q_k$
  - supplied to load – **used** solar system gain $Q_{ss,u}$

- **Annual energy savings $Q_{sav}$ [kWh/a]**
  - influenced by **operational efficiency** of given heat source (boiler) $\eta_{hs}$
  - consumption of electricity for pumps in solar system
  - base for primary enegy savings, emission savings

# Solar system parameters

- **Specific anual solar heat gain $q_{ss,u}$ [kWh/(m$^2$.a)]**
  - referenced to aperture area of solar collectors $A_a$
  - specific annual energy savings
  - economic parameter: savings / m$^2$ vs. investment / m$^2$

- **Solar coverage, solar fraction *f* [%]**

  *f* = 100 * used heat gain / heat demand (percentual coverage of demand)

- **Auxilliary energy consumption $Q_{aux,el}$ [kWh/a]**

  estimation: operation 2000 h x el. power for pumps, control, etc. [kW]

  usually < 1 % of gains

# Solar system parameters

- **back up energy** (boiler)

$$Q_{bu} = Q_d - Q_{ss,u} \qquad [kWh/a]$$

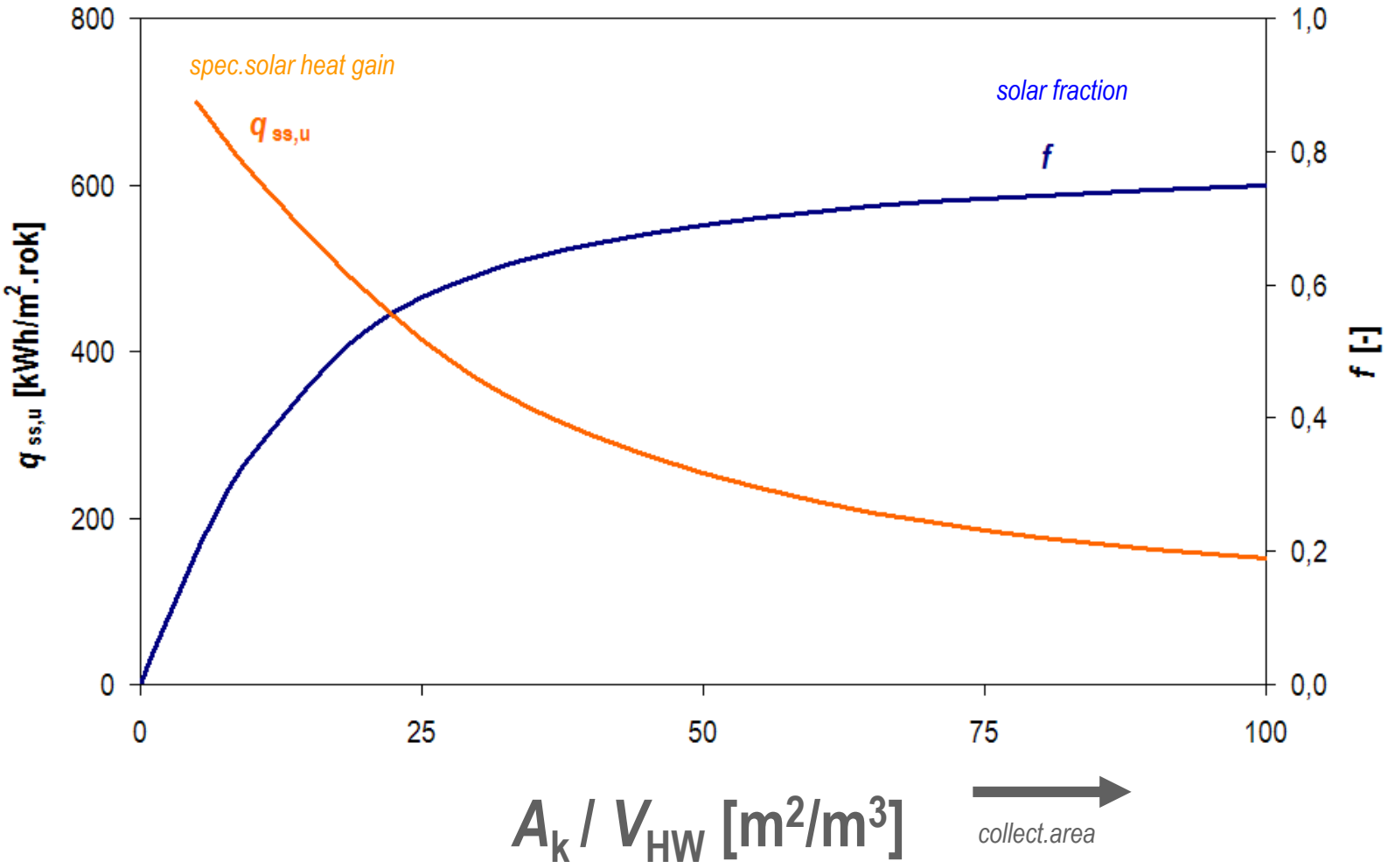
$Q_d$ heat demand - $Q_{ss,u}$ used solar system gain

- **solar fraction**

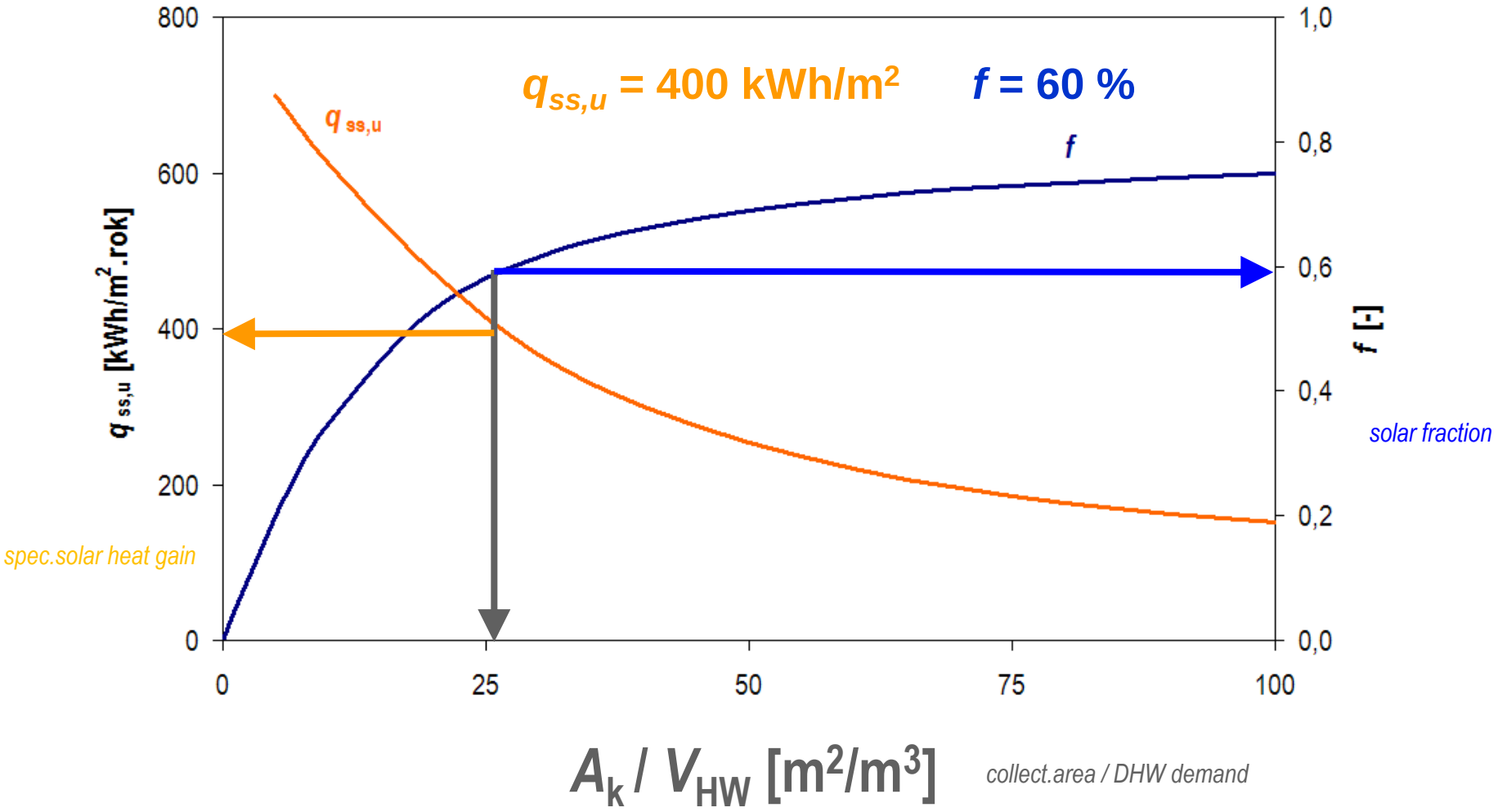
$$f = \frac{Q_{ss,u}}{Q_d} = 1 - \frac{Q_{bu}}{Q_d} = \frac{Q_{ss,u}}{Q_{ss,u} + Q_{bu}} \qquad [-]$$

- **specific solar heat gain** $q_{ss,u}$ [kWh/m$^2$.a]

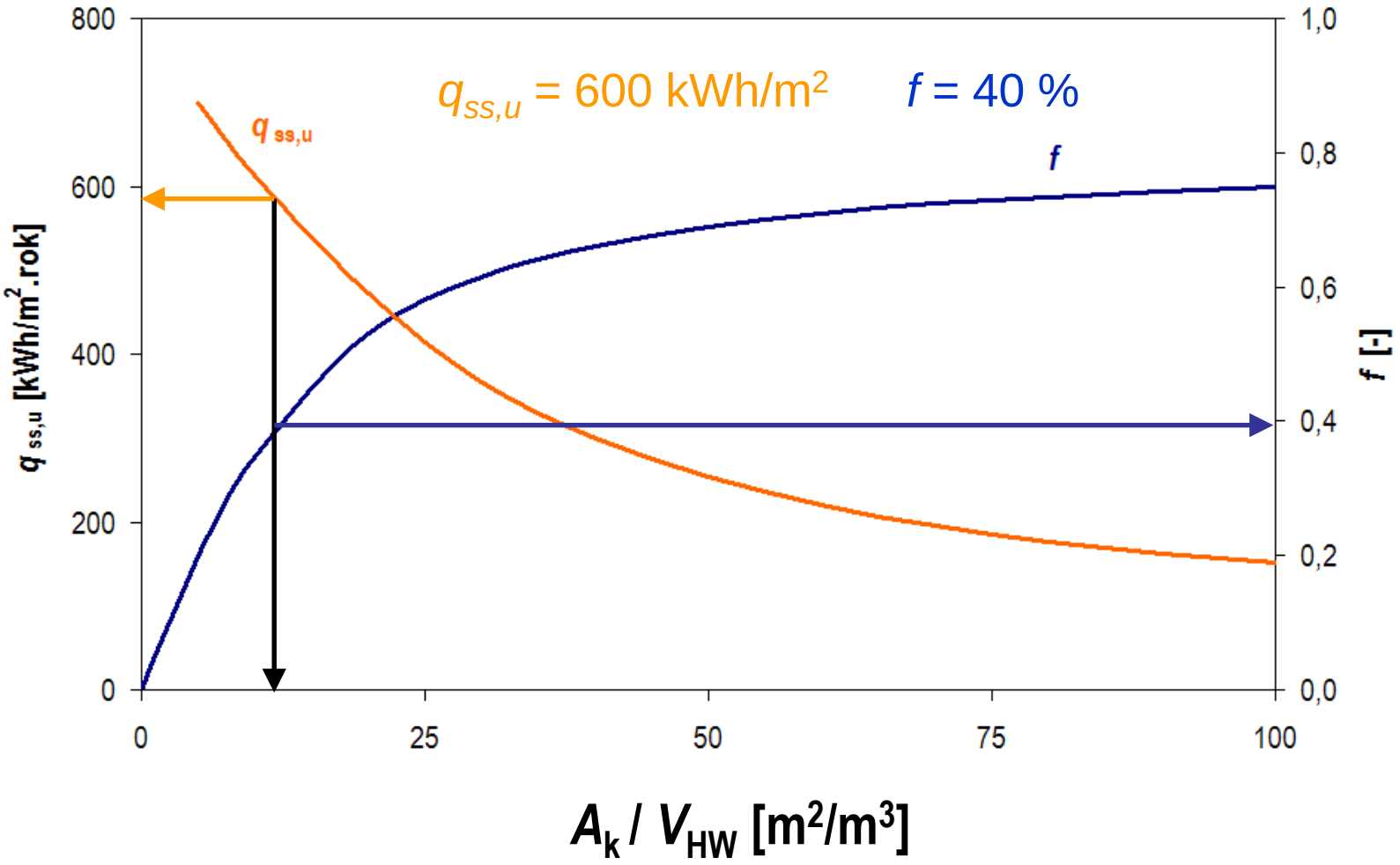
# Hot water example - balance



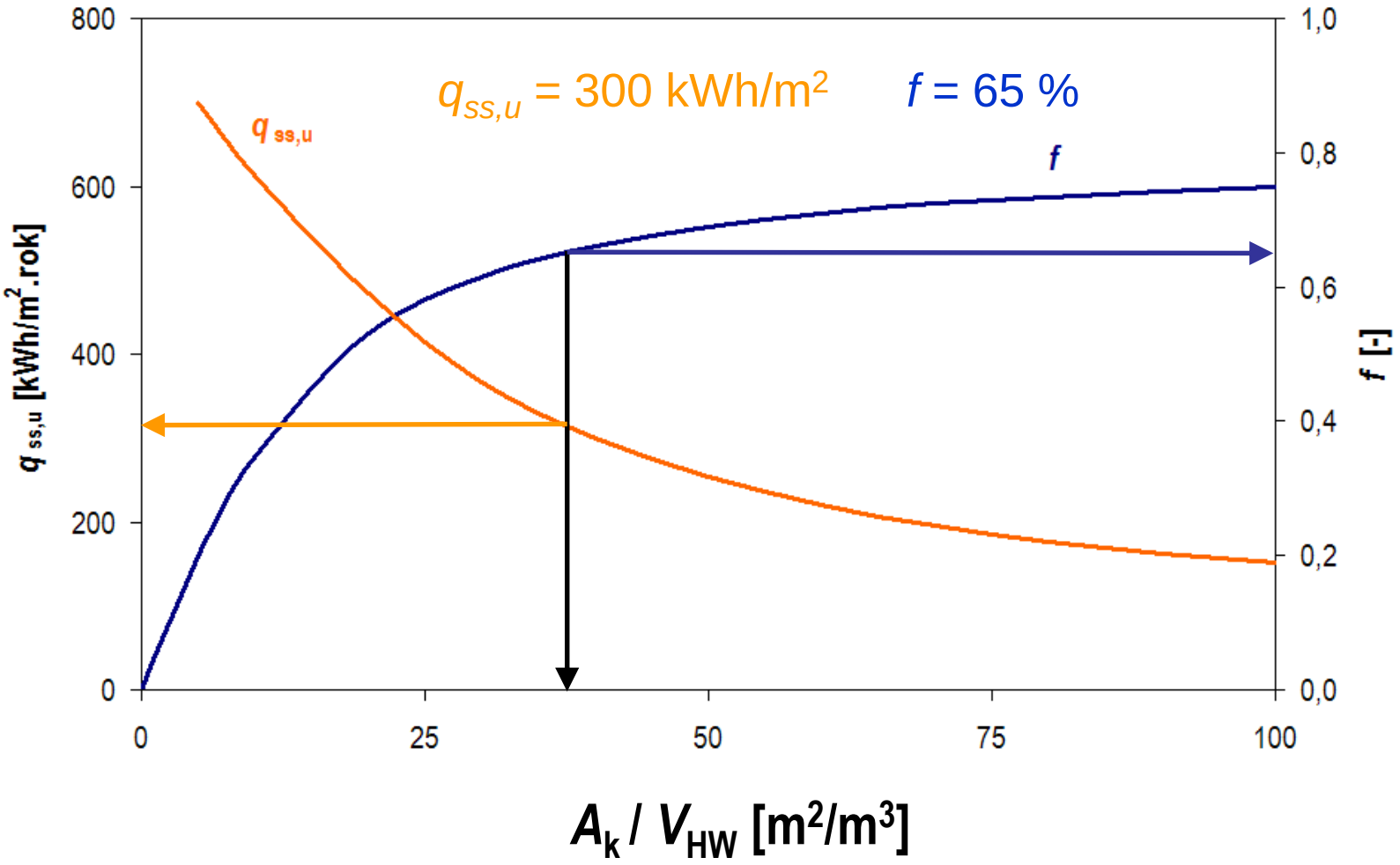
# Hot water example - balance



# Hot water example - balance

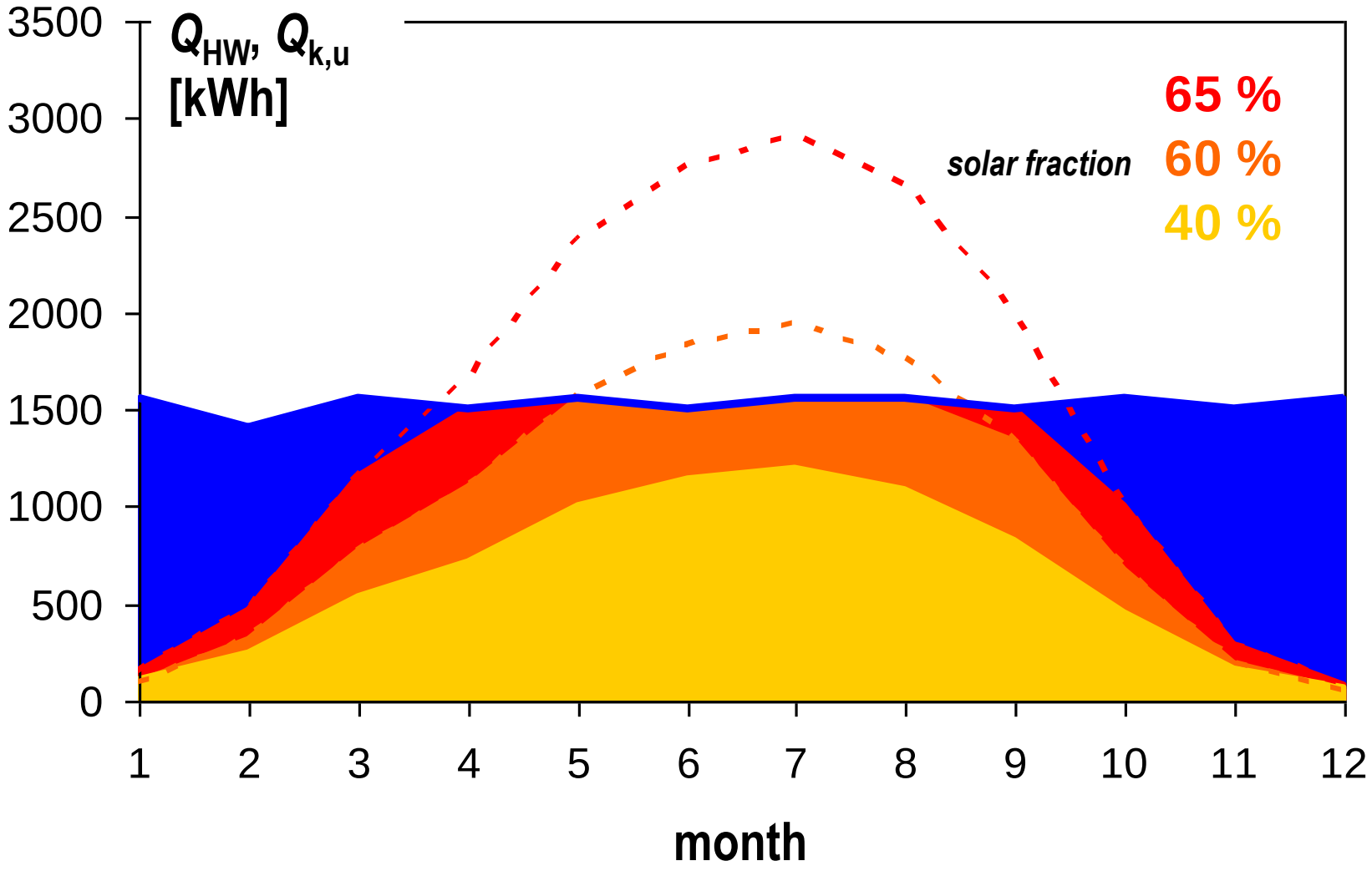


# Hot water example - balance

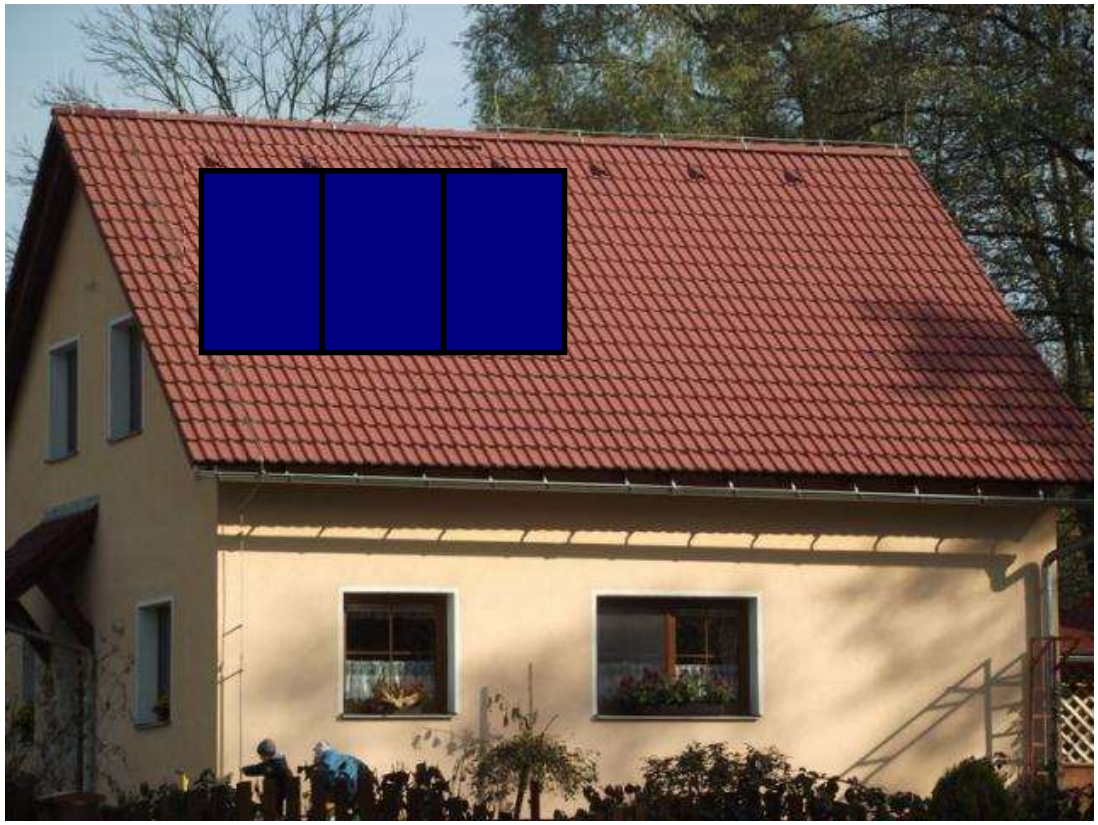



increase of solar fraction means decrease of specific heat gain

# Hot water example - balance



# Example 3 – solar DHW for family house



**2 or 3 collectors?**

# Example 3 – solar DHW system

- **monthly heat demand $Q_{d,HW}$ for DHW**
  - daily demand **8.4 kWh/day** x number of days

- **monthly available solar system gain $Q_{k,u}$**
  - calculation of collector efficiency for given climate condition $\eta_k$
  - calculation of monthly irradiation $H_{T,month}$

- **balance of demand x gain**

$$Q_{ss,u,month} = \min\left[0{,}9 \cdot \eta_k \cdot H_{T,month} \cdot A_k \cdot (1-p)\,;\, Q_{d,HW}\right]$$

# Example 3 – solar collector

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

# Example 3 – solar DHW system

| month | $t_{es}$ | $G_m$ | $\eta_k$ | $H_{T,month}$ |
|---|---|---|---|---|
| | °C | W/m$^2$ | – | kWh/m$^2$ |
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |

# Example 3 – solar DHW system

| měsíc | $t_{es}$ | $G_m$ | $\eta_k$ | $H_{T,month}$ |
|---|---|---|---|---|
| | °C | W/m$^2$ | – | kWh/m$^2$ |
| 1 | 2,2 | 418 | | |
| 2 | 3,4 | 489 | | |
| 3 | 6,5 | 535 | | |
| 4 | 12,1 | 527 | | |
| 5 | 16,6 | 521 | | |
| 6 | 20,6 | 517 | | |
| 7 | 22,5 | 512 | | |
| 8 | 22,6 | 515 | | |
| 9 | 19,4 | 516 | | |
| 10 | 13,8 | 488 | | |
| 11 | 7,3 | 427 | | |
| 12 | 3,5 | 387 | | |

# Example 3 – solar DHW system

| měsíc | $t_{es}$ | $G_m$ | $\eta_k$ | $H_{T,month}$ |
|---|---|---|---|---|
| | °C | W/m$^2$ | – | kWh/m$^2$ |
| 1 | 2,2 | 418 | 0,41 | |
| 2 | 3,4 | 489 | 0,48 | |
| 3 | 6,5 | 535 | 0,53 | |
| 4 | 12,1 | 527 | 0,57 | |
| 5 | 16,6 | 521 | 0,61 | |
| 6 | 20,6 | 517 | 0,64 | |
| 7 | 22,5 | 512 | 0,65 | |
| 8 | 22,6 | 515 | 0,65 | |
| 9 | 19,4 | 516 | 0,63 | |
| 10 | 13,8 | 488 | 0,57 | |
| 11 | 7,3 | 427 | 0,47 | |
| 12 | 3,5 | 387 | 0,40 | |

# Example 3 – solar DHW system

| month | $t_{es}$ | $G_m$ | $\eta_k$ | $H_{T,month}$ |
|---|---|---|---|---|
| | °C | W/m$^2$ | – | kWh/m$^2$ |
| 1 | 2,2 | 418 | 0,41 | 34,2 |
| 2 | 3,4 | 489 | 0,48 | 55,3 |
| 3 | 6,5 | 535 | 0,53 | 99,2 |
| 4 | 12,1 | 527 | 0,57 | 118,8 |
| 5 | 16,6 | 521 | 0,61 | 150,1 |
| 6 | 20,6 | 517 | 0,64 | 158,6 |
| 7 | 22,5 | 512 | 0,65 | 160,7 |
| 8 | 22,6 | 515 | 0,65 | 145,9 |
| 9 | 19,4 | 516 | 0,63 | 118,4 |
| 10 | 13,8 | 488 | 0,57 | 74,5 |
| 11 | 7,3 | 427 | 0,47 | 36,4 |
| 12 | 3,5 | 387 | 0,40 | 24,0 |

# Example 3 – solar DHW system

| | 2 collectors | 3 collectors | | 2 collectors | 3 collectors |
|---|---|---|---|---|---|
| month | $Q_{ku,month}$ | $Q_{ku,month}$ | $Q_{d,HW}$ | $Q_{ss,u}$ | $Q_{ss,u}$ |
| | kWh | kWh | kWh | kWh | kWh |
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| 6 | | | | | |
| 7 | | | | | |
| 8 | | | | | |
| 9 | | | | | |
| 10 | | | | | |
| 11 | | | | | |
| 12 | | | | | |

# Example 3 – solar DHW system

| | 2 collectors | 3 collectors | | 2 collectors | 3 collectors |
|---|---|---|---|---|---|
| měsíc | $Q_{ku,month}$ | $Q_{ku,month}$ | $Q_{d,HW}$ | $Q_{ss,u}$ | $Q_{ss,u}$ |
| | kWh | kWh | kWh | kWh | kWh |
| 1 | 41 | 61 | | | |
| 2 | 76 | 114 | | | |
| 3 | 151 | 227 | | | |
| 4 | 196 | 294 | | | |
| 5 | 263 | 394 | | | |
| 6 | 291 | 437 | | | |
| 7 | 302 | 452 | | | |
| 8 | 274 | 412 | | | |
| 9 | 214 | 321 | | | |
| 10 | 123 | 184 | | | |
| 11 | 50 | 75 | | | |
| 12 | 28 | 41 | | | |

# Example 3 – solar DHW system

| | 2 collectors | 3 collectors | | 2 collectors | 3 collectors |
|---|---|---|---|---|---|
| měsíc | $Q_{ku,month}$ | $Q_{ku,month}$ | $Q_{d,HW}$ | $Q_{ss,u}$ | $Q_{ss,u}$ |
| | kWh | kWh | kWh | kWh | kWh |
| 1 | 41 | 61 | 261 | | |
| 2 | 76 | 114 | 236 | | |
| 3 | 151 | 227 | 261 | | |
| 4 | 196 | 294 | 253 | | |
| 5 | 263 | 394 | 261 | | |
| 6 | 291 | 437 | 253 | | |
| 7 | 302 | 452 | 261 | | |
| 8 | 274 | 412 | 261 | | |
| 9 | 214 | 321 | 253 | | |
| 10 | 123 | 184 | 261 | | |
| 11 | 50 | 75 | 253 | | |
| 12 | 28 | 41 | 261 | | |

# Example 3 – solar DHW system

| | 2 collectors | 3 collectors | | 2 collectors | 3 collectors |
|---|---|---|---|---|---|
| měsíc | $Q_{ku,month}$ | $Q_{ku,month}$ | $Q_{d,HW}$ | $Q_{ss,u}$ | $Q_{ss,u}$ |
| | kWh | kWh | kWh | kWh | kWh |
| 1 | 41 | 61 | 261 | 41 | 61 |
| 2 | 76 | 114 | 236 | 76 | 114 |
| 3 | 151 | 227 | 261 | 151 | 227 |
| 4 | 196 | 294 | 253 | 196 | 253 |
| 5 | 263 | 394 | 261 | 261 | 261 |
| 6 | 291 | 437 | 253 | 253 | 253 |
| 7 | 302 | 452 | 261 | 261 | 261 |
| 8 | 274 | 412 | 261 | 261 | 261 |
| 9 | 214 | 321 | 253 | 214 | 253 |
| 10 | 123 | 184 | 261 | 123 | 184 |
| 11 | 50 | 75 | 253 | 50 | 75 |
| 12 | 28 | 41 | 261 | 28 | 41 |

# Example 3 – results

- **total heat demand $Q_{d,HW}$**
  - **3076 kWh/a**
- **total solar system usable gain $Q_{ss,u}$**
  - 2 collectors **1914 kWh/a**
  - 3 collectors **2243 kWh/a**
- **solar fraction**
  - 2 collectors **62 %**
  - 3 collectors **73 %**

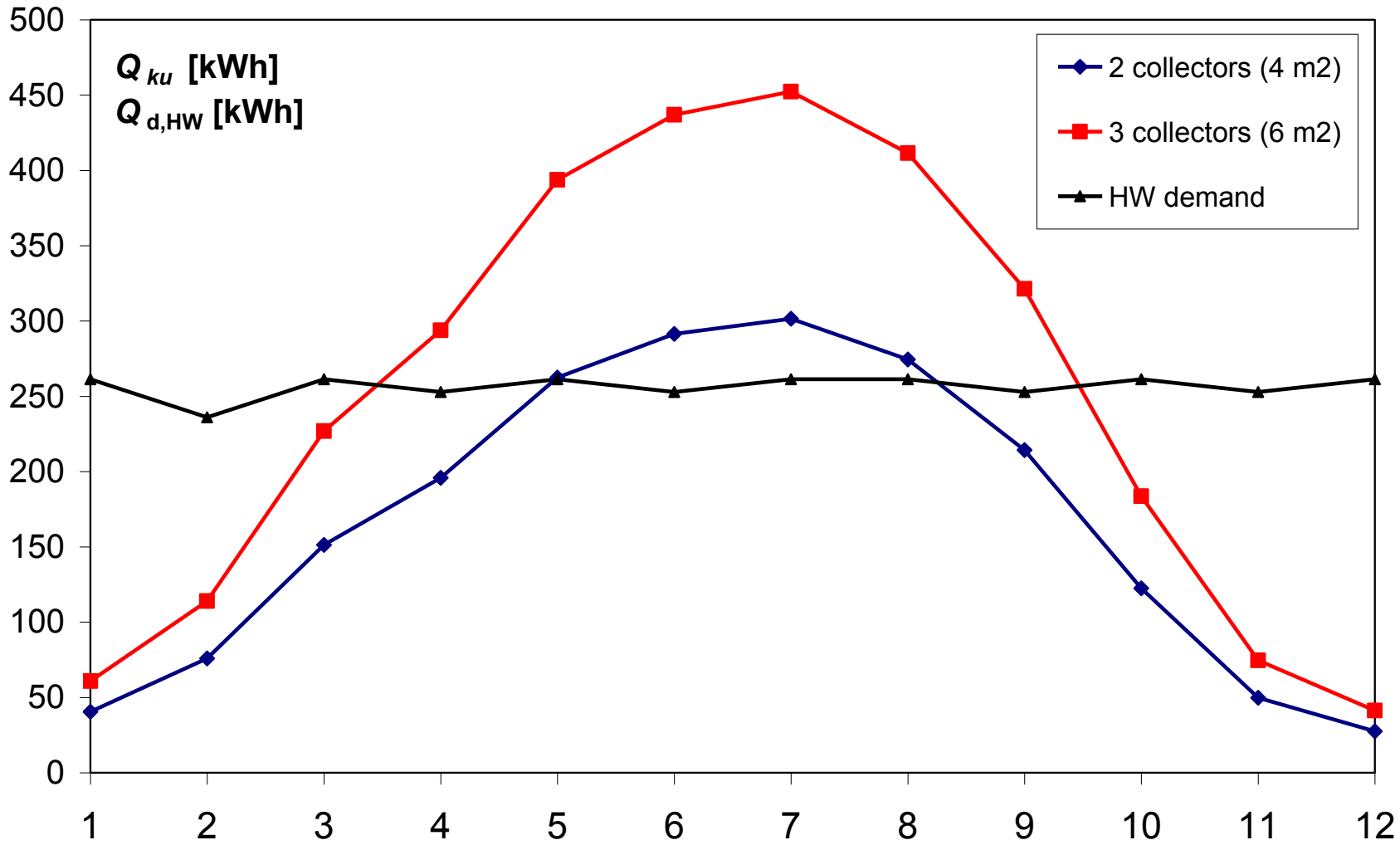
**specific heat gains**

**479 kWh/m².a** **economic**

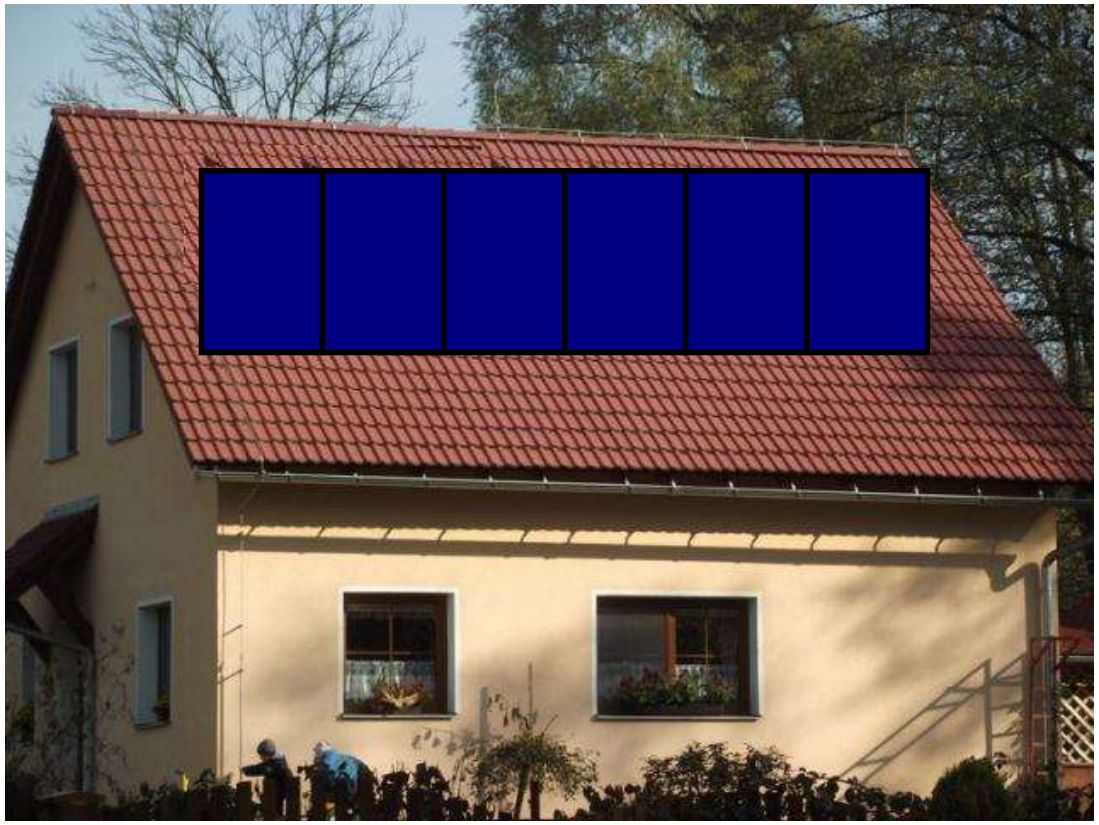
**374 kWh/m².a** **ecologic**

**what is better?**

# Example 3 – results



# Example 4 – solar combisystem



**5 or 6 collectors ?**

# Example 4 – solar combisystem

| měsíc | $t_{es}$ | $G_m$ | $\eta_k$ | $H_{T,month}$ |
|---|---|---|---|---|
| | °C | W/m$^2$ | – | kWh/m$^2$ |
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |

# Example 4 – solar combisystem

| month | $t_{es}$ | $G_m$ | $\eta_k$ | $H_{T,month}$ |
|---|---|---|---|---|
| | °C | W/m$^2$ | – | kWh/m$^2$ |
| 1 | 2,2 | 418 | | |
| 2 | 3,4 | 489 | | |
| 3 | 6,5 | 535 | | |
| 4 | 12,1 | 527 | | |
| 5 | 16,6 | 521 | | |
| 6 | 20,6 | 517 | | |
| 7 | 22,5 | 512 | | |
| 8 | 22,6 | 515 | | |
| 9 | 19,4 | 516 | | |
| 10 | 13,8 | 488 | | |
| 11 | 7,3 | 427 | | |
| 12 | 3,5 | 387 | | |

# Example 4 – solar combisystem

| měsíc | $t_{es}$ | $G_m$ | $\eta_k$ | $H_{T,month}$ |
|---|---|---|---|---|
| | °C | W/m$^2$ | – | kWh/m$^2$ |
| 1 | 2,2 | 418 | 0,30 | |
| 2 | 3,4 | 489 | 0,38 | |
| 3 | 6,5 | 535 | 0,44 | |
| 4 | 12,1 | 527 | 0,49 | |
| 5 | 16,6 | 521 | 0,52 | |
| 6 | 20,6 | 517 | 0,56 | |
| 7 | 22,5 | 512 | 0,57 | |
| 8 | 22,6 | 515 | 0,57 | |
| 9 | 19,4 | 516 | 0,55 | |
| 10 | 13,8 | 488 | 0,48 | |
| 11 | 7,3 | 427 | 0,37 | |
| 12 | 3,5 | 387 | 0,28 | |

# Example 4 – solar combisystem

| měsíc | $t_{es}$ | $G_m$ | $\eta_k$ | $H_{T,month}$ |
|---|---|---|---|---|
| | °C | W/m$^2$ | – | kWh/m$^2$ |
| 1 | 2,2 | 418 | 0,30 | 34,2 |
| 2 | 3,4 | 489 | 0,38 | 55,3 |
| 3 | 6,5 | 535 | 0,44 | 99,2 |
| 4 | 12,1 | 527 | 0,49 | 118,8 |
| 5 | 16,6 | 521 | 0,52 | 150,1 |
| 6 | 20,6 | 517 | 0,56 | 158,6 |
| 7 | 22,5 | 512 | 0,57 | 160,7 |
| 8 | 22,6 | 515 | 0,57 | 145,9 |
| 9 | 19,4 | 516 | 0,55 | 118,4 |
| 10 | 13,8 | 488 | 0,48 | 74,5 |
| 11 | 7,3 | 427 | 0,37 | 36,4 |
| 12 | 3,5 | 387 | 0,28 | 24,0 |

# Example 4 – solar combisystem

| | 5 collectors | 6 collectors | | 5 collectors | 6 collectors |
|---|---|---|---|---|---|
| měsíc | $Q_{ku,month}$ | $Q_{ku,month}$ | $Q_{d,HW+SH}$ | $Q_{ss,u}$ | $Q_{ss,u}$ |
| | kWh | kWh | kWh | kWh | kWh |
| 1 | | | | | |
| 2 | | | | | |
| 3 | | | | | |
| 4 | | | | | |
| 5 | | | | | |
| 6 | | | | | |
| 7 | | | | | |
| 8 | | | | | |
| 9 | | | | | |
| 10 | | | | | |
| 11 | | | | | |
| 12 | | | | | |

# Example 4 – solar combisystem

| | 5 collectors | 6 collectors | | 5 collectors | 6 collectors |
|---|---|---|---|---|---|
| měsíc | $Q_{ku,month}$ | $Q_{ku,month}$ | $Q_{d,HW+SH}$ | $Q_{ss,u}$ | $Q_{ss,u}$ |
| | kWh | kWh | kWh | kWh | kWh |
| 1 | 73 | 88 | | | |
| 2 | 151 | 181 | | | |
| 3 | 316 | 379 | | | |
| 4 | 417 | 500 | | | |
| 5 | 566 | 679 | | | |
| 6 | 635 | 762 | | | |
| 7 | 659 | 791 | | | |
| 8 | 601 | 721 | | | |
| 9 | 465 | 558 | | | |
| 10 | 257 | 309 | | | |
| 11 | 96 | 115 | | | |
| 12 | 48 | 57 | | | |

# Example 4 – solar combisystem

| | 5 collectors | 6 collectors | | 5 collectors | 6 collectors |
|---|---|---|---|---|---|
| měsíc | $Q_{ku,month}$ | $Q_{ku,month}$ | $Q_{d,HW+SH}$ | $Q_{ss,u}$ | $Q_{ss,u}$ |
| | kWh | kWh | kWh | kWh | kWh |
| 1 | 73 | 88 | 1521 | | |
| 2 | 151 | 181 | 1294 | | |
| 3 | 316 | 379 | 1246 | | |
| 4 | 417 | 500 | 888 | | |
| 5 | 566 | 679 | 636 | | |
| 6 | 635 | 762 | 253 | | |
| 7 | 659 | 791 | 261 | | |
| 8 | 601 | 721 | 261 | | |
| 9 | 465 | 558 | 542 | | |
| 10 | 257 | 309 | 882 | | |
| 11 | 96 | 115 | 1205 | | |
| 12 | 48 | 57 | 1445 | | |

# Example 4 – solar combisystem

| | 5 collectors | 6 collectors | | 5 collectors | 6 collectors |
|---|---|---|---|---|---|
| měsíc | $Q_{ku,month}$ | $Q_{ku,month}$ | $Q_{d,HW+SH}$ | $Q_{ss,u}$ | $Q_{ss,u}$ |
| | kWh | kWh | kWh | kWh | kWh |
| 1 | 73 | 88 | 1521 | 73 | 88 |
| 2 | 151 | 181 | 1294 | 151 | 181 |
| 3 | 316 | 379 | 1246 | 316 | 379 |
| 4 | 417 | 500 | 888 | 417 | 500 |
| 5 | 566 | 679 | 636 | 566 | 636 |
| 6 | 635 | 762 | 253 | 253 | 253 |
| 7 | 659 | 791 | 261 | 261 | 261 |
| 8 | 601 | 721 | 261 | 261 | 261 |
| 9 | 465 | 558 | 542 | 465 | 542 |
| 10 | 257 | 309 | 882 | 257 | 309 |
| 11 | 96 | 115 | 1205 | 96 | 115 |
| 12 | 48 | 57 | 1445 | 48 | 57 |

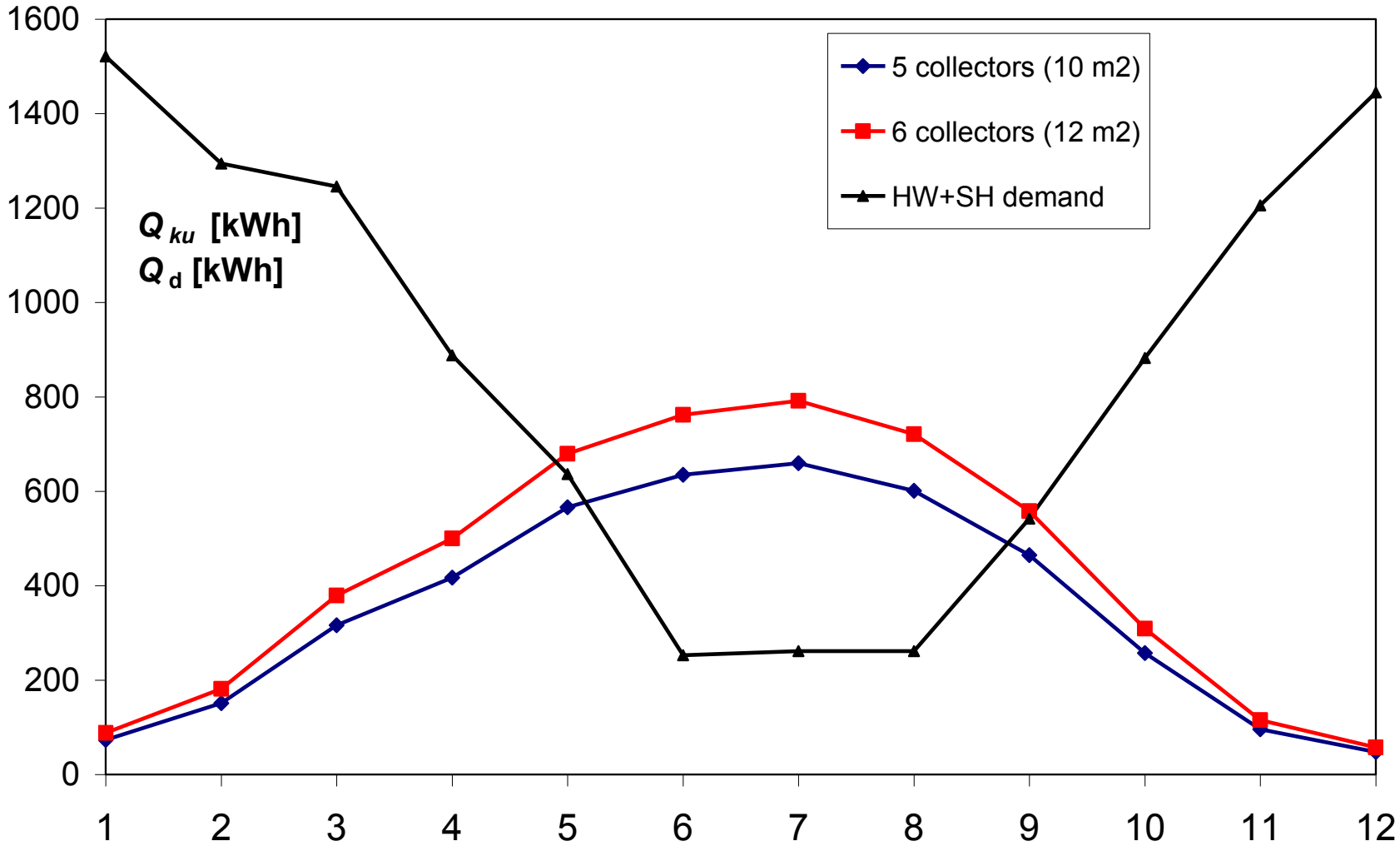
# Example 4 – solar combisystem

- **total heat demand $Q_d$**
  - **10434 kWh/a**
- **total solar system usable gain $Q_{ss,u}$**
  - 5 collectors **3164 kWh/a**
  - 6 collectors **3583 kWh/a**

| **solar fraction** | | **specific heat gains** |
|---|---|---|
| 5 collectors | **30 %** | **316 kWh/m$^2$.a** |
| 6 collectors | **34 %** | **299 kWh/m$^2$.a** |

**what is better?**

# Example 4 – solar combisystem

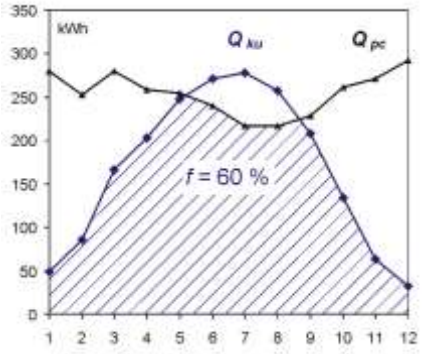


# Performance of solar systems

- hot water
- combisystems
- pool water

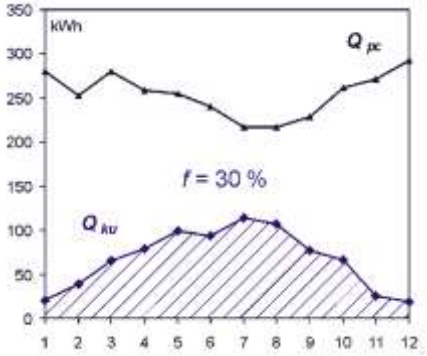
# Solar hot water systems

- **family houses**
  - (3 to 6 $m^2$; 250 to 400 l), solar fraction 50 to 70 %
  - solar yields **300 to 400 kWh/$m^2$.a**




- **residential sector, hotels, ...**
  - (from 25 to 200 $m^2$; 1 to 8 $m^3$), solar fraction 40 to 50 %
  - solar yields **400 to 500 kWh/$m^2$.a**

- **hot water preheating**
  - solar fraction 20 to 40 %
  - solar yields **500 to 600 kWh/$m^2$.a**



# Solar system in Meziboří – DHW

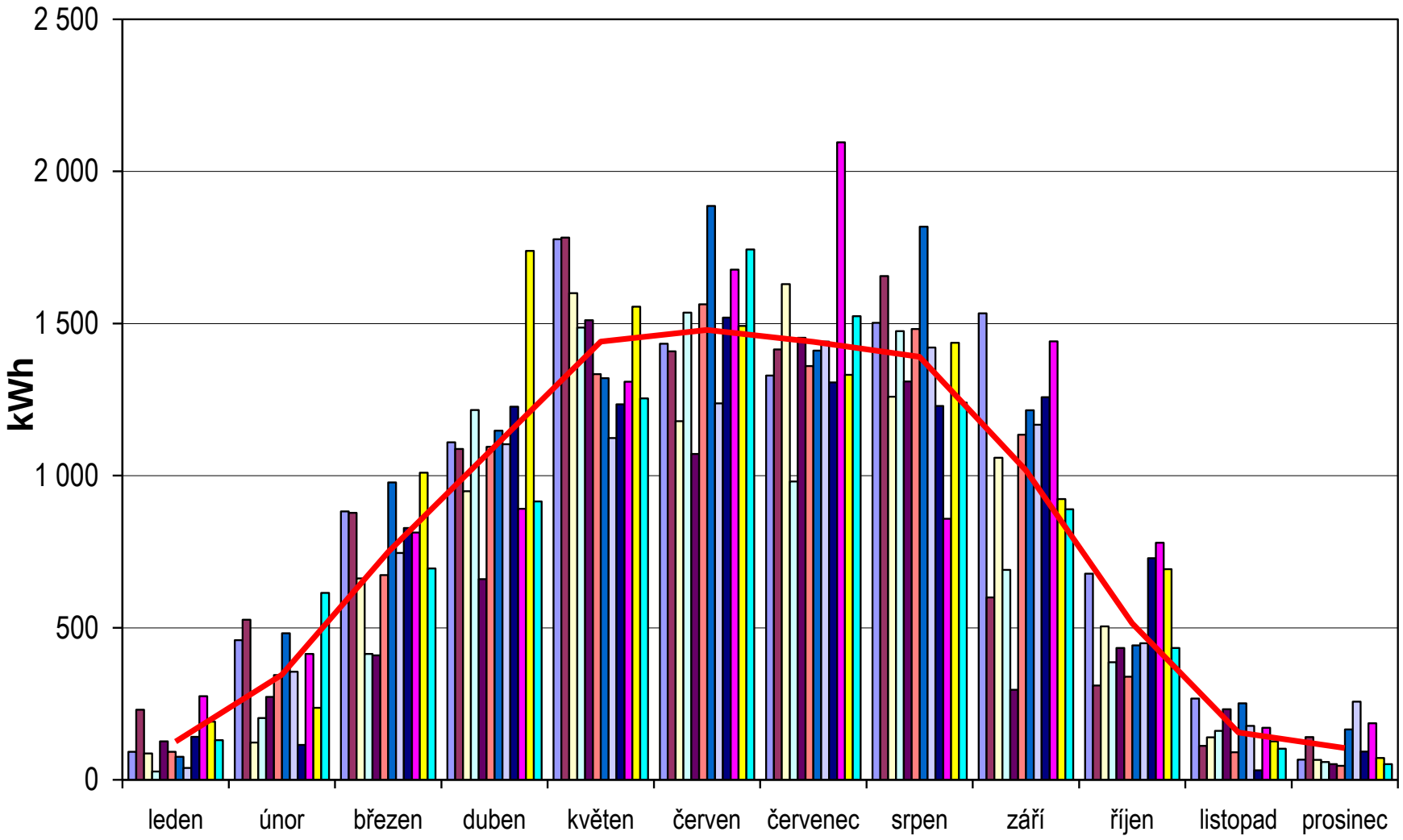
company Doterm Servis
administration building

installation 1996
offices
workshop
accommodation

measurement for more than12 years

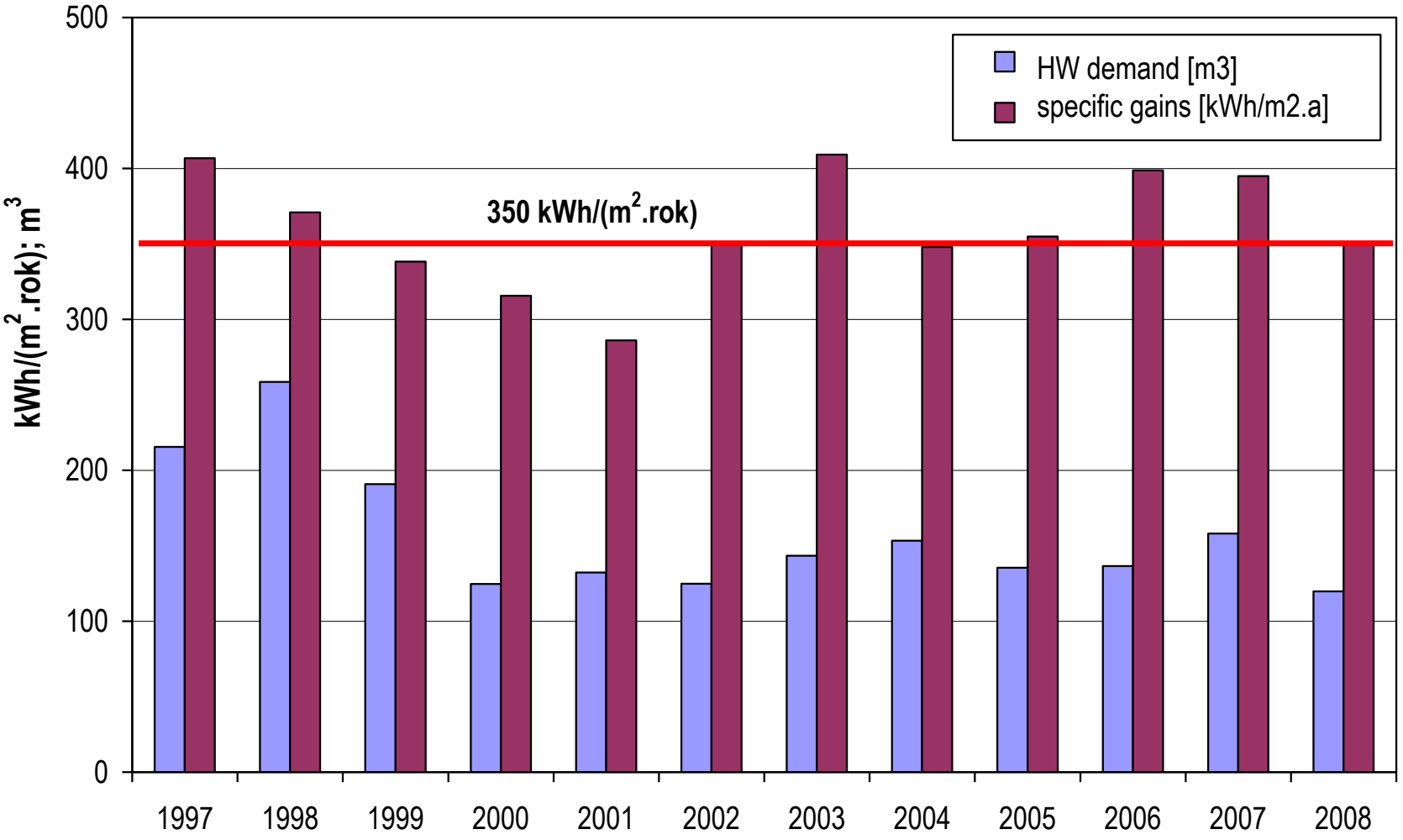
15 pcs flat-plate solar collectors Heliostar = 27 $m^2$

# Solar system in Meziboří – DHW



# Solar system in Meziboří – DHW

HW demand: 130 to 250 $m^3$ (high share of heat losses)

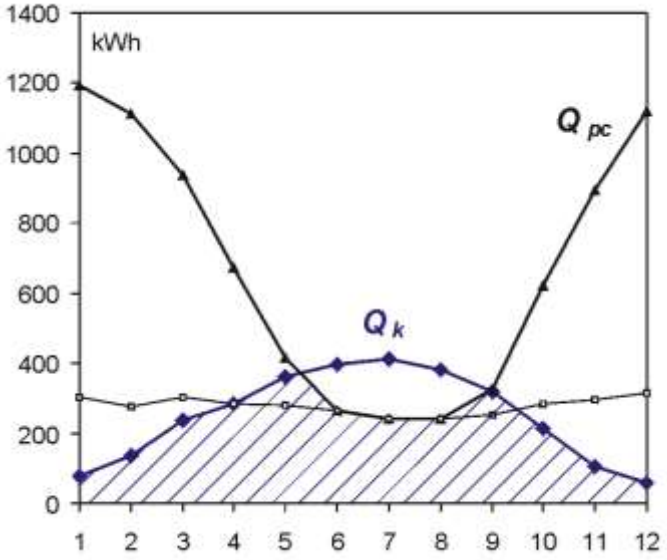


# Solar combisystems

# Solar combisystems

- **family houses**
  - (6 to 12 $m^2$; 1000 to 4 000 l)
  - solar fraction: standard houses 10 to 20 %
    low energy, passive houses 20 to 40 %
  - solar yields **250 to 350 kWh/$m^2$.a**

- **block of flats**
  - (40 to 200 $m^2$; 4 to 16 $m^3$)
  - solar fraction 10 to 20 %
  - solar yields **350 to 450 kWh/$m^2$.a**

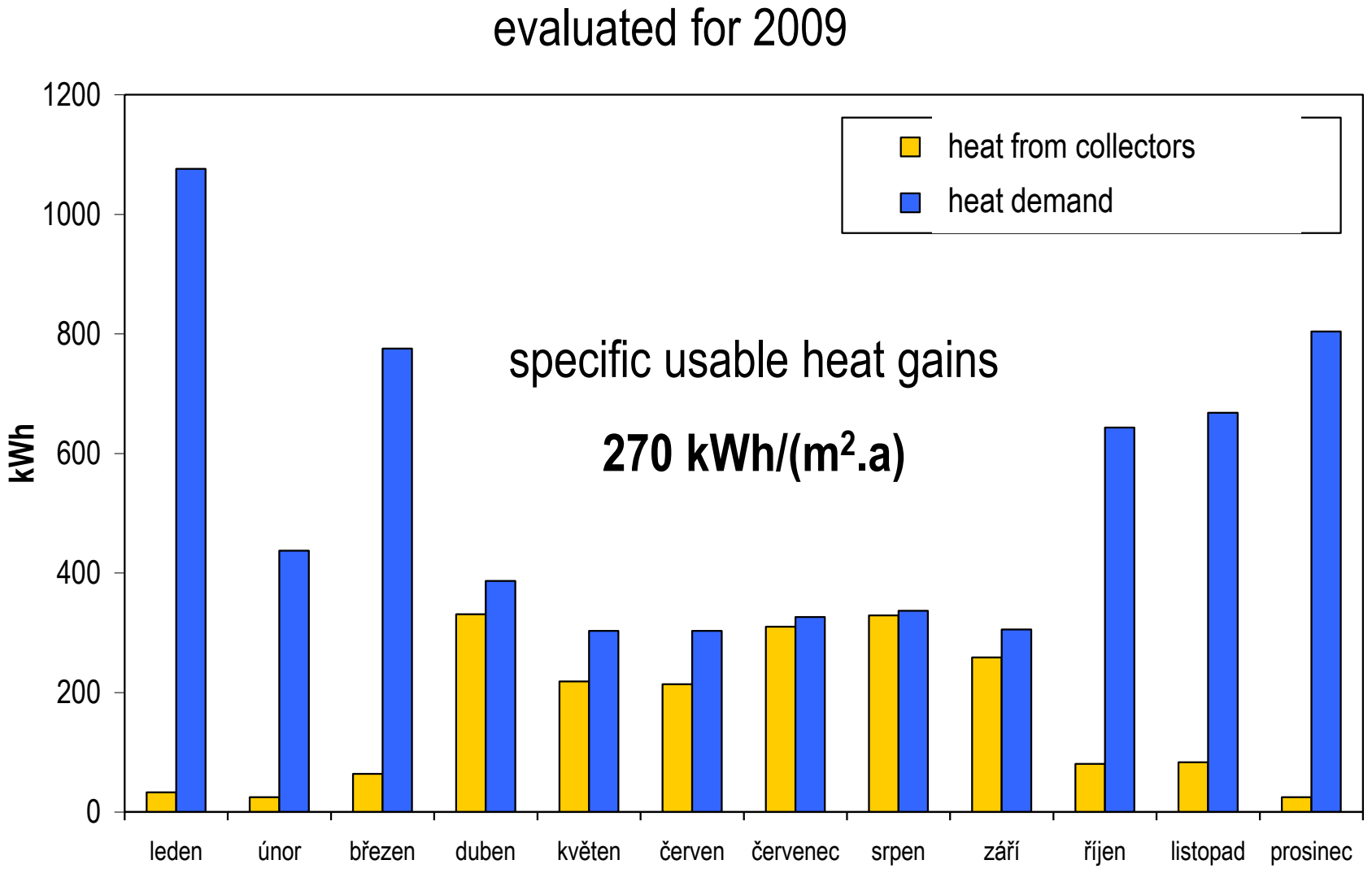


# Solar system in Mnichovice (HW+SH)

family house, 4 persons, heat loss 5,2 kW

solar collector area 7,3 $m^2$, slope 60°

# Solar system in Mnichovice (HW+SH)



# Swimming pool heating

# Swimming pool heating

- whole year – covered pools
- seasonal use – open, outdoor pools
- covering the heat losses from pool water surface, heating of fresh cold water
- pool is the storage

- specific energy yields above 500 kWh/m$^2$.a

  *(if whole year operation)*

# Outdoor pool Rusava


**installation 1984-1985**

557 $m^2$ solar collectors SP 80/08

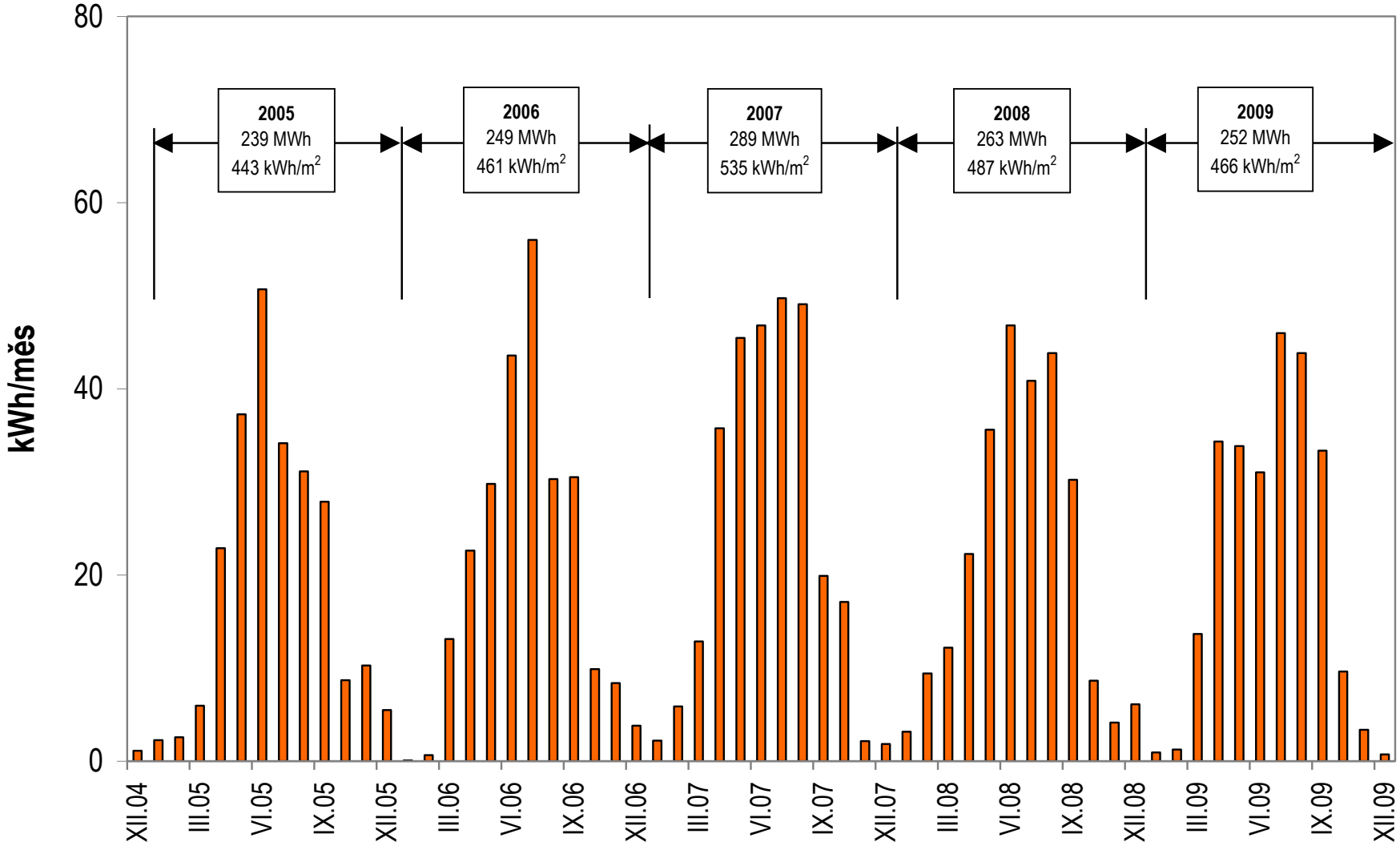
**retrofit 2002**

540 $m^2$ solar collectors Ekostart

# Solar system in Rusava

# Solar system in Rusava

# Annual yields 450 to 540 kWh/m$^2$



# Operation 1.5. – 30.9. 350 to 400 kWh/m²