THE DIMENSIONING OF SYSTEMS FOR DOMESTIC WATER HEATING

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DESIGN OBJECTIVES

- In sunny climates, the common design goal is either to supply the hot water consumption fully from solar energy, or to supply full coverage for most of the year and use a back-up heater (often an electrical element immersed in the solar tank) for only a few weeks or months per year.

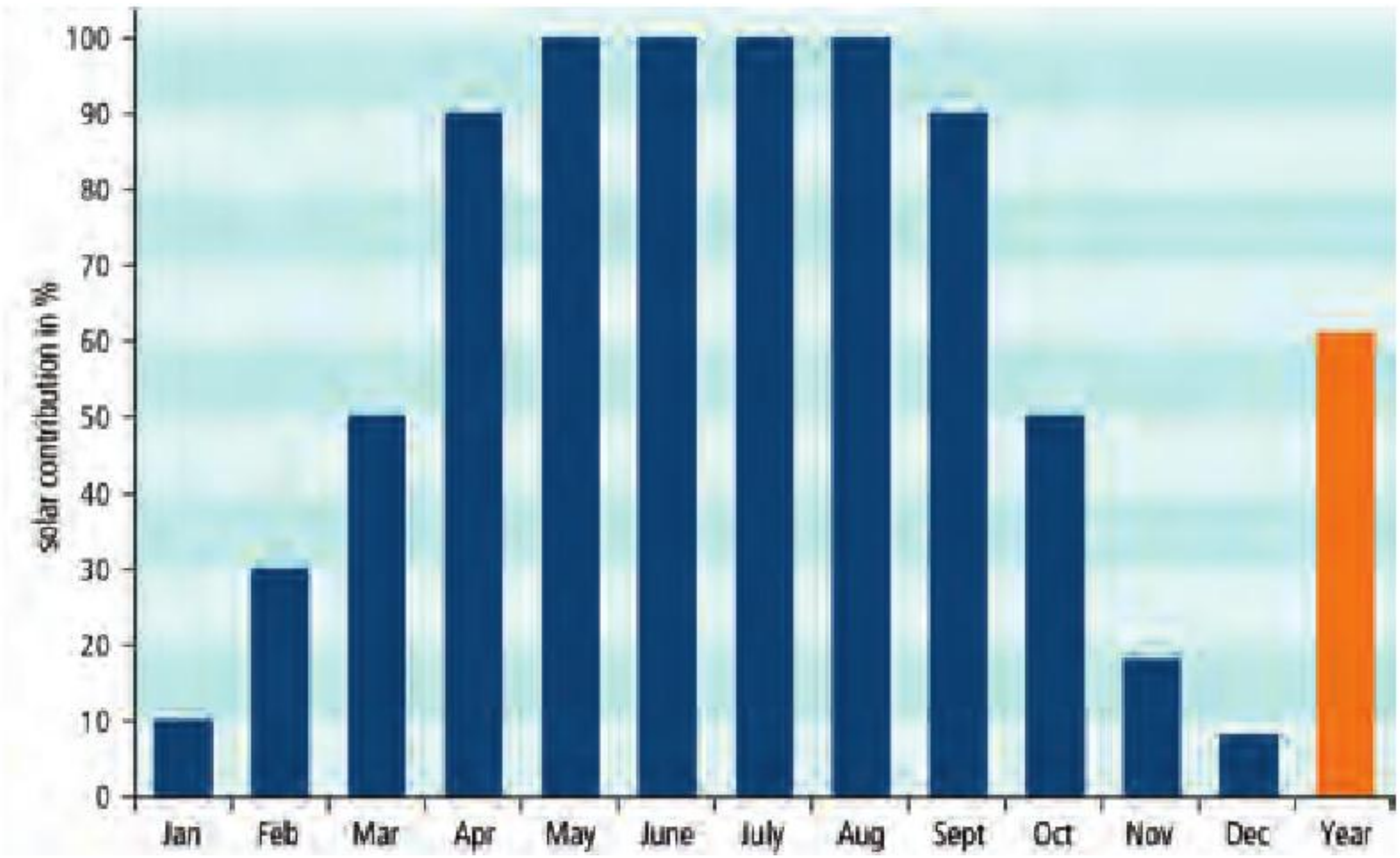
SOLAR FRACTION

- The solar fraction is described as the ratio of solar heat yield to the total energy requirement for hot water heating:

$$SF = \frac{Q_S}{Q_S + Q_{aux}} \times 100$$

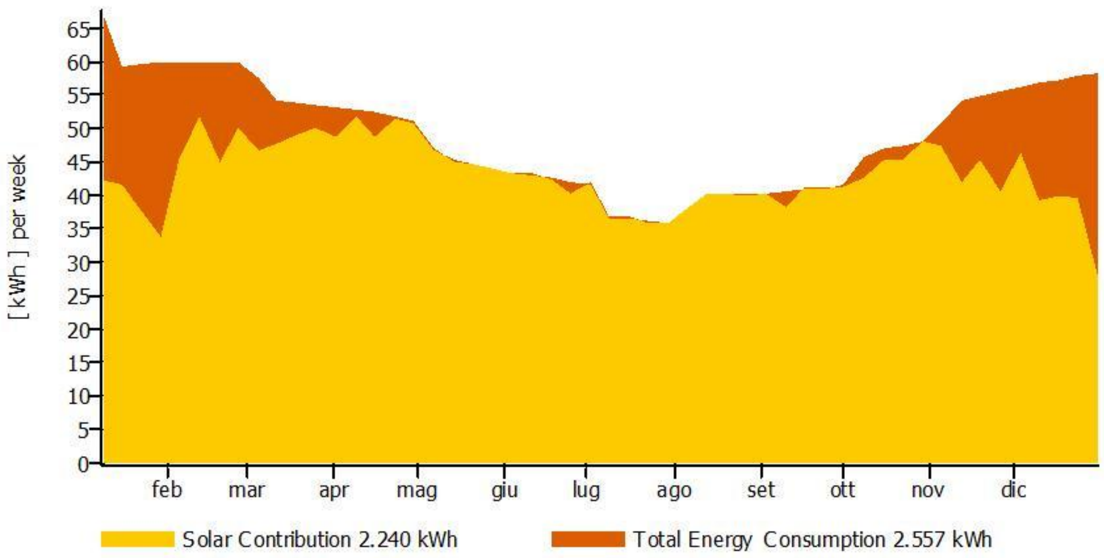
- Where SF is the solar fraction (%),
- Q_S is the solar heat yield (kWh),
- Q_{aux} is the auxiliary heating requirement (kWh).
- The higher the solar fraction in a solar energy system, the lower the amount of fossil energy required for auxiliary heating: in the extreme case (SF = 100%) none at all.

Solar fraction for each month for a system in Northern Europe (55°N), designed to cover the hot water demand fully in the summer months.



- When a system is properly designed, for instance to cover almost the complete demand in the summer months in central Europe, the addition of extra collector areas would not lead to correspondingly higher output. In periods with high irradiation, the system would produce excess heat, which would lead not only to frequent high thermal loads on the collectors (stagnation), but also to a lower efficiency (additional costs are higher than additional yield). In periods with lower irradiation, the output would be higher but the total annual output per square meter of collector would be lower than with the original system.

Solar Energy Consumption as Percentage of Total Cosumption



SYSTEM EFFICIENCY

- The system efficiency gives the ratio of solar heat yield to the global solar irradiance on the absorber surface with respect to a given period of time, for example one year:

$$SE = \frac{\dot{Q}_S}{E_G A} \times 100$$

- SE is the system efficiency (%),
- Q_S is the solar heat yield (kWh/a),
- E_G is the total yearly solar irradiance (kWh/m 2a),
- *A is the absorber surface area (m).*

- If the absorber surface area and the irradiance are known, and if the solar heat yield is measured (heat meter), the system efficiency can be determined:

Example:

$A = 6 \text{ m}^2$

$E_G = 1000 \text{ kWh/m}^2\text{a}$ (central Europe)

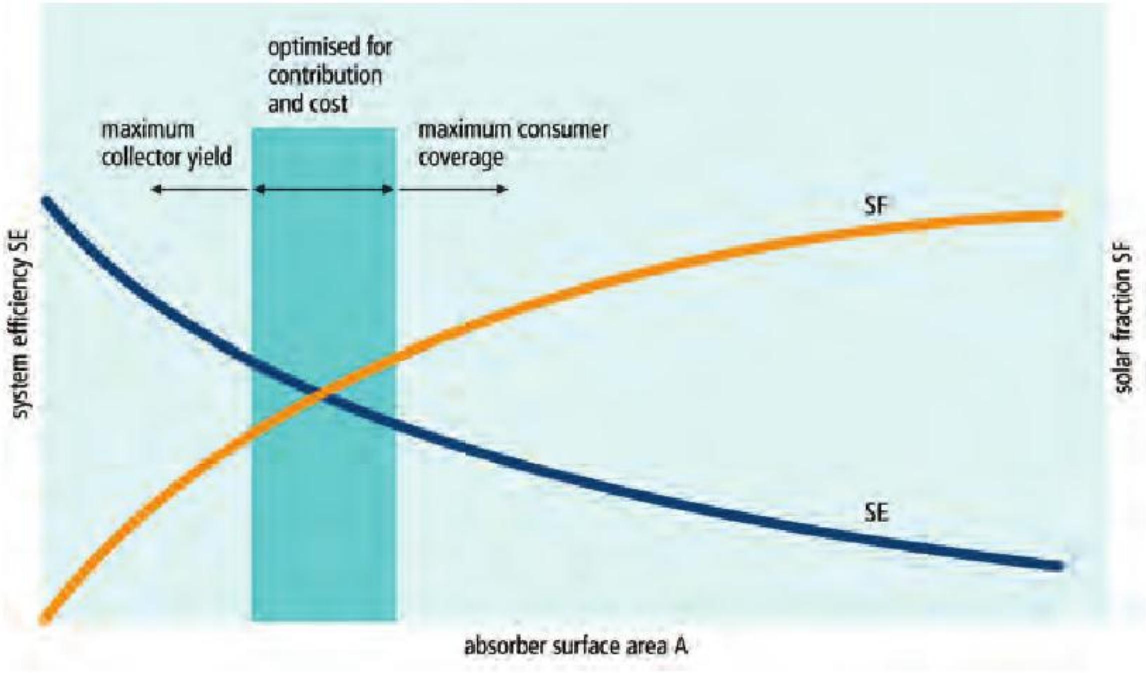
$\dot{Q}_s = 2100 \text{ kWh/a}$

Then the system efficiency is given by

$$\text{SE} = \frac{2100 \text{ kWh} \times \text{m}^2 \times \text{a}}{1000 \text{ kWh} \times \text{a} \times 6\text{m}^2} \times 100 = 35\%$$

Relation between SF and SE

- The system efficiency is strongly dependent on the solar fraction. It is higher at lower solar fractions (when the solar water heater size is small compared with the hot water demand). If the solar fraction is increased by increasing the collector area, the system efficiency is reduced, and every further kilowatt-hour that is gained becomes more expensive. This counter-effect of the two variables can be seen below:



STEP 1: DETERMINATION OF HOT WATER CONSUMPTION

- The hot water consumption, V_{HW}, of those living in the house is a key variable for system planning, and if it cannot be measured, it should be estimated as closely as possible.
- When determining the requirements, a check should be made on the possibilities of saving domestic water (for example by the use of water- and energy saving fittings).
- A lower water consumption means a smaller solar energy system and hence a lower investment.

- During the design of solar energy systems for one- and two-family houses, the following average values can be used for estimating the hot water

1 × hand washing (40°C; 104°F)	3 l (0.8 gallons)
1 × showering (40°C; 104°F)	35 l (9.3 gallons)
1 × bathing (40°C; 104°F)	120 l (31.7 gallons)
1 × hair washing	9 l (2.4 gallons)
Cleaning	3 l (0.8 gallons) per person per day
Cooking	2 l (0.5 gallons) per person per day
1 × dishwashing (50°C; 122°F)	20 l (5.3 gallons)
1 × washing machine (50°C; 122°F)	30 l (7.9 gallons)

Depending on the fittings in the household, the following average consumption values per person per day can be calculated (usage temperature of hot water approximately 45°C; 113°F):

■ low consumption	20–30 l (5–8 gallons)
■ average consumption	30–50 l (8–13 gallons)
■ high consumption	50–70 l (13–18 gallons)

System components

- Collector surface area,
- domestic water store volume,
- solar circuit pipework,
- heat exchanger,
- circulating pump,
- expansion vessel
- and safety valve.

Example

- In the following, all the components for a thermal solar energy system for heating the domestic water for a four-person household in the UK will be dimensioned:
- We assume an average hot water consumption of 50 l per person per day (45°C), and a requirement to supply the dishwasher and the washing machine with solar-heated water.
- According to the information from the user the dishwasher and washing machine operate on average twice per week.

- Taking into account the different hot water temperatures, the daily hot water consumption is then calculated as follows:

$$V_{HW} = 4 \text{ persons} \times 50\ \text{l}\ (45°\text{C}) + 16\ \text{l}\ (45°\text{C}) = 216\ \text{l}\ (45°\text{C}) \text{ per day}$$

Step 2: Hot water heat requirement

- The heat requirement, Q_{HW}, can be determined from the hot water consumption according to the following equation:

$$Q_{HW} = V_{HW} c_W \Delta\theta$$

where V_{HW} is the average hot water quantity (l or kg), c_W is the specific heat capacity of water (= 1.16 Wh/kgK), and $\Delta\theta$ is the temperature difference between hot and cold water (K).

- In our example the necessary daily heat requirement for heating 216 l of water from 10°C (we assume this to be the cold water temperature for this example) to 45°C is given by:

$$
\begin{aligned}
Q_{HW} &= 216\ \text{kg} \times 1.16\ \text{Wh/kg K} \times (45 - 10)\ \text{K} \\
&= 8770\ \text{Wh} \\
&= 8.77\ \text{kWh per day}
\end{aligned}
$$

Note that, depending on the domestic/drinking water regulations, the actual temperature of the hot water delivered should in some countries be higher, for instance 60°C (140°F). In such cases, the water will be mixed at the tapping point. The hot water supply system will have to deliver a smaller amount of water at the high temperature, which will however have the same energy content. This amount is calculated as follows:

$$V_{\theta 2} = \frac{\theta_1 - \theta_c}{\theta_2 - \theta_c} \times V_{\theta 1}$$

where θ_1 is the old temperature level, θ_2 is the new temperature level, θ_c is the cold water temperature, $V_{\theta 1}$ is the volume of water at the old temperature level, and $V_{\theta 2}$ is the volume of water at the new temperature level.

For example, the amount of water at 60°C (140°F) equivalent to the above-mentioned 216 l (57 gallons) at 45°C (113°F), using a cold water temperature of 10°C (50°F), is calculated as follows:

$$V_{60} = \frac{45 - 10}{60 - 10} \times 216 = 151 \text{ l}$$

HEAT LOSSES IN PIPING AND STORES

The significance of thermal insulation is often underestimated. In the following, estimates are made of the possible thermal losses from the solar circuit, the circulation lines and the solar store.

HEAT LOSSES IN INSULATED PIPES

It is possible to make a relatively good estimate of the losses if we consider only the heat conduction through the thermal insulation.[19]

The heat losses can be formulated as follows:

$$Q_{pipe} = \frac{2\pi\lambda\Delta\theta}{\ln(D_{wd}/D_{pipe})} \quad \text{(W/m)}$$

Example:

λ = 0.04 W/mK (mineral wool)

D_{wd} = 54 mm

D_{pipe} = 18 mm

$\Delta\theta$ = 30 K

In this way Q_{pipe} is calculated as

$$Q_{pipe} = \frac{2\pi \times 0.04\ \text{W} \times 30\ \text{K}}{\ln(54\ \text{mm}/18\text{mm})\text{mK}} = 6.9\ \text{W/m}$$

With a total solar circuit length of 20 m and approximately 2000 operating hours per annum, heat losses of $\dot{Q}_{pipe}$ = 6.9 W/m × 20 m × 2000 h/a = 276 kWh/a. This corresponds to an approximate annual yield for a solar energy plant with 5 m² of glazed flat-plate collectors of 15% ($\dot{Q}_S$ = 5 m² × 1000 kWh/m²a × 0.35 = 1750 kWh/a).

HEAT LOSSES FROM STORES

The heat losses from a solar store increase in proportion to the area of its upper area, A, and the temperature difference between the store and the surroundings, $\Delta\theta$:

$$\dot{Q}_{St} \approx A\Delta\theta$$

With the help of the heat loss coefficient k in W/m^2K, the following equation is derived:

$$\dot{Q}_{St} = kA\Delta\theta \text{ (W)}$$

For stores the kA value is normally given in W/K.

Example:

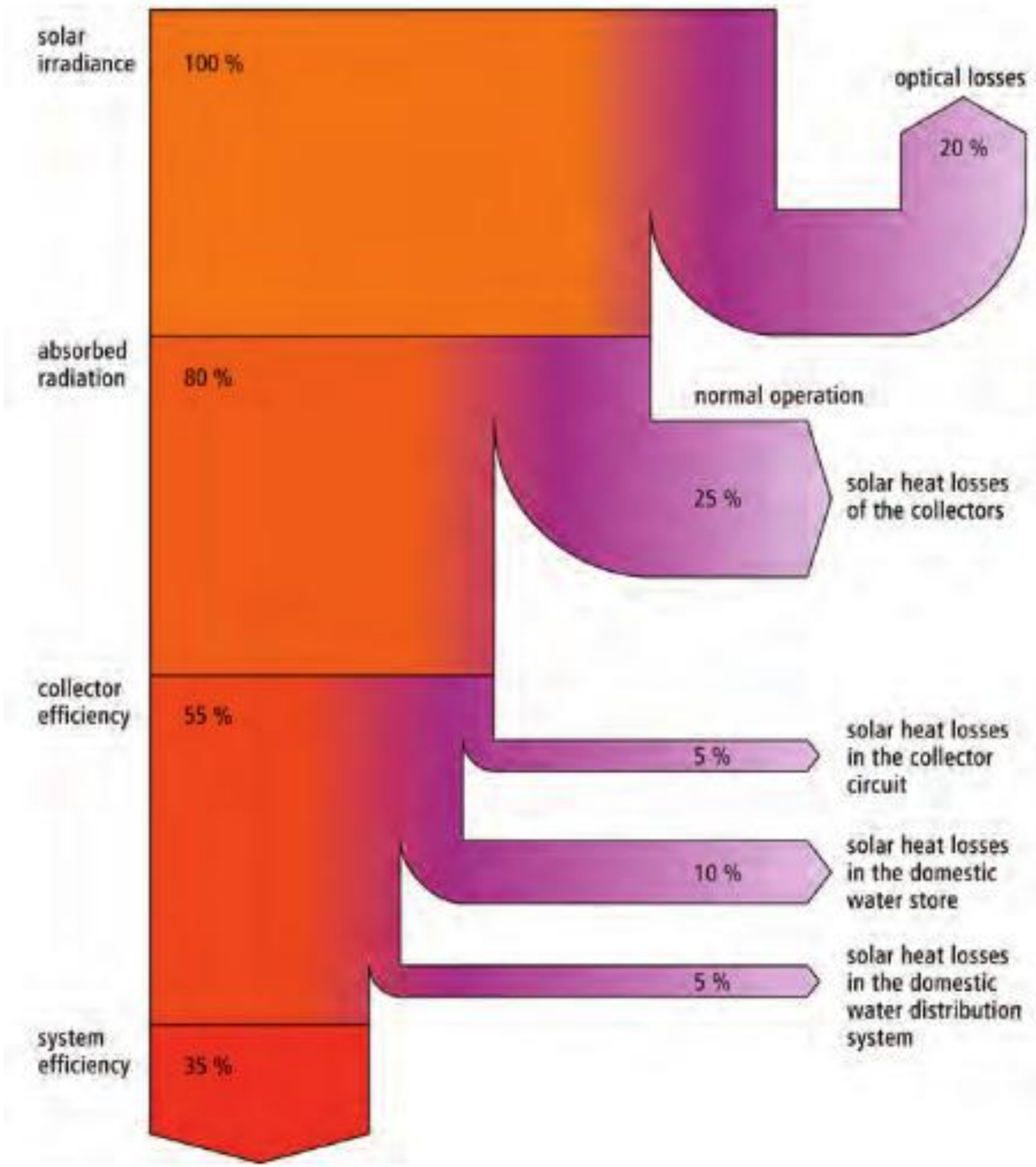
kA value = 1.6 W/K
$\Delta\theta$ = 30 K

$$\dot{Q}_{St} = 1.6 \text{ W/K} \times 30 \text{ K} = 48 \text{ W}$$

Over the course of a year this store has heat losses of

$$\dot{Q}_{St} = 48 \text{ W} \times 24 \text{ h/d} \times 365 \text{ days/a} \approx 420 \text{ kWh/a}$$

In the above case the heat losses in the store thereby correspond with the solar gain of about 1.2 m^2 of collector surface.


solar irradiance
100 %
optical losses
20 %
absorbed radiation
80 %
normal operation
25 %
solar heat losses of the collectors
collector efficiency
55 %
5 %
solar heat losses in the collector circuit
10 %
solar heat losses in the domestic water store
5 %
solar heat losses in the domestic water distribution system
system efficiency
35 %

3.5.2.6 STEP 3: DESIGN AND DIMENSIONING OF SYSTEM COMPONENTS

There are four different methods:

- rough determination of size with an approximation formula
- detailed calculation of the individual components
- graphical design with nomographs
- computer-aided design with simulation programs.

ROUGH DETERMINATION OF SIZE WITH AN APPROXIMATION FORMULA

COLLECTOR SURFACE AREA

For a system designed for a *temperate climate*, a rough estimate for the essential system components can be made under the following assumptions:

- Average hot water requirement, V_{HW} = 35–65 litres (9.3–17.2 gallons) (45°C; 113°F) per person per day.
- Yearly average solar fraction = approximately 60% (covering almost the complete hot water demand in the summer months).
- Collector at optimal or almost optimal orientation and tilt angle (see section 1.1.3).
- No or little shading.
- Design goal is to cover the load almost completely in the months with high

The rule of thumb for such situations is:

1–1.5 m² (10.8–16.2 ft²) of glazed flat-plate collector area per person (E_G = 1000 kWh/m²a)
0.7–1 m² (7.5–10.8 ft²) of evacuated tube collector surface per person (E_G = 1000 kWh/m²a)

For a *tropical climate*, the collector area can be estimated under the following assumptions:

- Average hot water requirement, V_{HW} = 35–65 litres (9.3–17.2 gallons) (45°C; 113°F) per person per day.
- Favourable solar irradiance conditions.
- Yearly average solar fraction = approximately 80% (auxiliary heating is necessary only in a few months).
- Collector at optimal or almost optimal orientation and tilt angle (see section 1.1.3).
- No or little shading.

The rule of thumb for such situations is:

0.35–0.6 m² (3.8–6.5 ft²) of glazed flat-plate collector area per person (E_G = 2000 kWh/m²a)

In our example this approximation formula leads to a required glazed flat-plate collector surface area of 1.4–2.4 m².

For different irradiation levels (see Chapter 1), these values may be scaled. For instance, when the irradiance is 1700 kWh/m²a, the collector area must be 1.2 times larger.

DOMESTIC WATER STORE VOLUMES AND HEAT EXCHANGERS

In general, in order to bridge over a few sunless days without any auxiliary heating, the store volume should be designed to be 1–2 times the daily hot water consumption. In our example of a consumption of 216 l (57 gallons) per day, this leads to a store volume of 200–400 l (52.8–105.7 gallons). For the dimensioning of internal heat exchangers the following approximation formulae apply:

- Finned tube heat exchanger: 0.35 m^2 exchanger surface area per m^2 of collector surface area.
- Plain tube heat exchanger: 0.20 m^2 exchanger surface area per m^2 of collector surface area.

For our example this means that, in the selection of a store with a built-in plain tube heat exchanger, it should have a surface area of about 0.8–1.2 m^2 (4–6 × 0.2 m^2).

Collector surface area (m^2)	Total length (m)				
	10	20	30	40	50
Up to 5	15/I	15/I	15/I	15/I	15/I
6–12	18/I	18/I	18/I	18/I	18/I
13–16	18/I	22/I	22/I	22/I	22/I
17–20	22/I	22/I	22/I	22/I	22/I
21–25	22/I	22/II	22/II	22/II	22/III
26–30	22/II	22/II	22/III	22/III	22/III

The Roman characters identify the respective circulation pumps. I ≡ 30–60 W power consumption. II, III ≡ 45–90 W.

Table 3.1.
Solar circuit pipe diameter in relation to collector surface area and length of solar circuit pipes[20]

System volume (l)	Collector surface area (m^2)	System height (m)					
		2.5	5	7.5	10	12.5	15
18	5	12	12	12	12	18	18
20	7.5	12	12	12	18	25	35
23	10	12	12	18	25	35	35
24	12.5	12	18	25	35	35	35
25	15	18	25	35	35	35	50
29	17.5	25	35	35	35	50	50
35	20	25	35	35	50	50	50
37	25	35	35	50	50	50	80
40	30	35	50	50	50	80	80

DETAILED CALCULATION OF THE INDIVIDUAL COMPONENTS

- **COLLECTOR SURFACE AREA**
  - calculated heat requirement,
  - taking into account the solar radiation,
  - an average system efficiency
  - desired solar fraction, the required collector or

- Calculated heat requirement, Q_{HW}= 8.77 kWh per day .
- Yearly solar radiation,
  - (central European climate)
  - Solar irradiance at α= 45° and β= 40°.
    - E_G= 1000 kWh/m²/year
- Average system efficiency, η_{sys} = 0.35
- Desired solar fraction,
    - SF = 60% for temperate climates,
    - 80% for tropical climates

Absorber surface area is calculated as follows:

$$\text{Absorber surface} = \frac{365 \text{ days} \times 8.77 \text{ kWh per day} \times 0.6}{1000 \text{ kWh/m}^2\text{a} \times 0.35}$$

$$\approx 5.5\text{m}^2 \text{ (59.2 ft}^2\text{) for temperate climates}$$

$=3.7\text{m}^2$ for tropical climate