financed by
Austrian
Development Cooperation

Dimensioning and Design of Solar Thermal Systems

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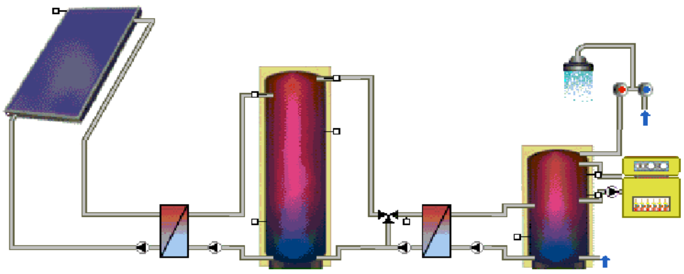
Hot Water System – Hotel



Hot water consumption

Number of beds (single rooms/ double rooms)	120
Average occupancy	80%
Restaurant (hot water demand/day)	160

Cold water temperature	20°C
Rule of thumb: corresponds to the average annual air temperature	
Hot water temperature (storage)	50°C
Climate data for design	June
(for high solar fraction: 75 - 80%)	

Calculation and Dimensioning of:

1. Daily hot water demand
2. Hot water storage capacity
3. Collector area

1 DIMENSIONING of domestic hot water systems

1.1 Hot water demand

The hot water demand is decisive for the dimensioning of a domestic hot water (DHW) solar system. However, this depends on the users' habits. For example, if a person is used to have a shower rather than a bath, the daily hot water demand is significantly lower than if a bath is frequently taken. The daily hot water demand can be estimated as shown in the table below.

Table 1: Hot water demand for different users at a hot water temperature of 50 °C.

		Low demand (litres)	Medium demand (litres)	High demand (litres)
Residential buildings	per person and day	30	50	60
Sport facilities	per shower	20	30	50
Accommodation	per bed	20	40	60

1.2 The hot water storage tank capacity

When the daily hot water demand has been determined, the volume of the storage tank can be specified. It should be some 0.8 to 1.2 fold the daily demand for regions with high solar radiation and 2 to 2.5 fold the daily demand for regions with lower solar radiation (central and northern Europe) respectively, so that consumption peaks can be met well and cloudy days can be compensated.

Examples

For a hotel with 120 beds (B) and an annual occupancy (O) of 80% and an average hot water demand (HWD) of 40 litres per person (P), the daily demand (DD) is 3,840 litres. In addition a hot water demand of 160 litre per day is needed for the restaurant (HWD_R).

The volume of the storage tank (V_{St}) is thus calculated as follows:

$$V_{St} = [(B * O * HDW) + HDW_R] * 1.2$$

$$= [(120 * 0.8 * 40) + 160] \times 1.2 = 4{,}800 \text{ litres}$$

As the manufacturers do not offer tanks in every possible size, the choice has to be made among those generally available on the market. However, it is recommended that the storage tank capacity is not less than 90% and not more than 120% of the calculated volume.

1.3 Energy capacity of a storage unit

The energy storage capacity of a water storage unit at uniform temperature is given by:

$$Q_s = (m\ C_p)\ \Delta T$$

Q_s	total heat capacity of the storage tank	[kWh]
m	volume of the storage tank	[m³]
C_p	heat capacity of water	[1.16 kWh/m³K]
ΔT	temperature difference - hot water temperature and cold water temperature [K]	

1.4 Radiation data

Johannesburg – Global radiation in kWh/m²

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
197	169	165	142	128	112	121	146	162	186	188	201	1917

Cape Town – Global radiation in kWh/m²

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
124	186	163	108	81	67	75	95	124	172	198	231	1624

Maputo – Global radiation in kWh/m²

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
189	165	162	136	122	107	115	135	148	165	171	199	1814

Windhoek – Global radiation in kWh/m²

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
131	188	199	171	162	143	159	182	204	225	233	234	2231

1.5 Collector efficiency curve

The following figure shows an efficiency curve of a simple flat plate collector.

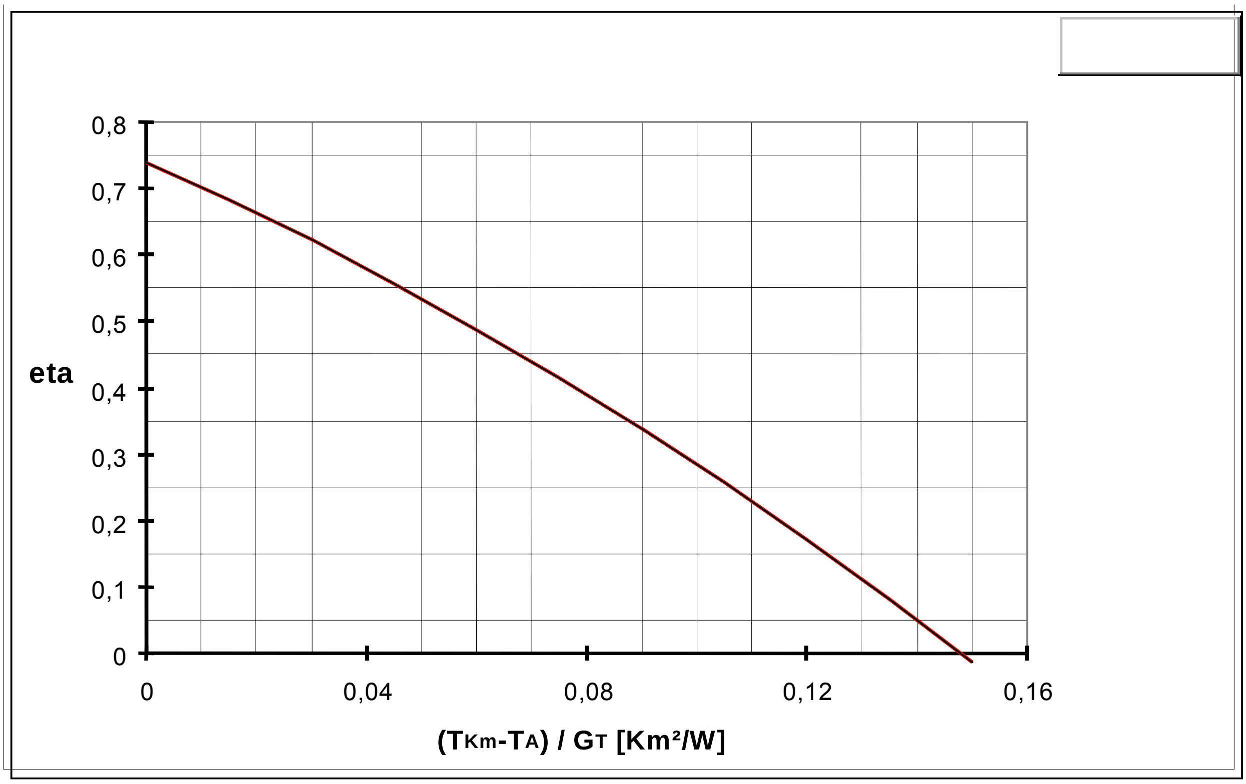


Figure 1: Efficiency curve of a simple flat plate collctor

1.6 Location, tilt and orientation of collectors

The most usual place to install collectors is the roof area. If it is not possible to mount the collectors on the roof, they can also be mounted on a suitable frame near the house, they can be integrated into an earth bank, or mounted on a flat roof. However, in each case attention should be paid to keeping the pipes to and from the tank as short as possible.

Collector orientation
As a general rule, the collector should be facing the equator. That means in the southern hemisphere **facing north** and in the northern hemisphere facing south. A deviation of 45° to the east or west is nevertheless possible, as it does not reduce the total system yield significantly (see figure below).
In addition, care should be taken that the collectors are not shaded at any time of the year, either by trees, buildings or other collectors.

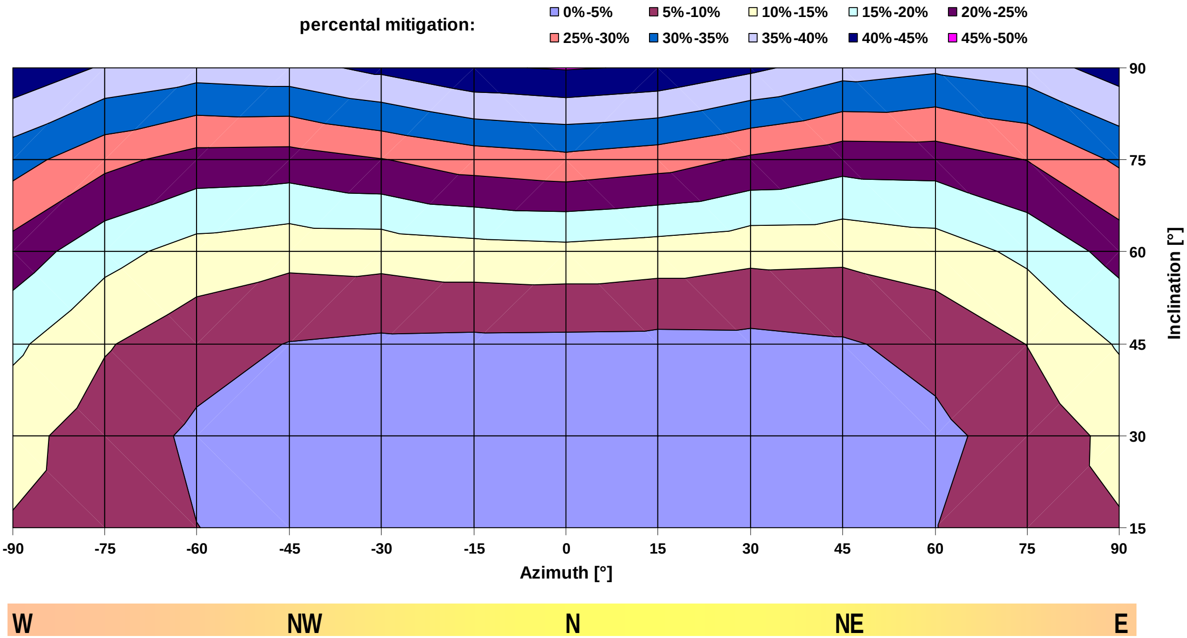


Figure 2: Variations of the annual solar yield in [kWh/m²·a] in **Johannesburg** related to different orientations and azimuth angles

Table 2: Variations of the annual solar yield in [kWh/m²·a] in **Johannesburg** related to different orientations and azimuth angles. The calculations are based on a solar hot water system with 3m² collector area and a daily hot water consumption of 150 litre.

Azimuth [°]		Inclination [°]					
		15	30	45	60	75	90
W	-90	887.9	867.0	824.5	757.1	665.9	549.7
	-75	912.3	909.6	879.6	817.0	722.3	595.1
	-60	932.3	940.9	914.7	854.0	754.9	614.7
NW	-45	947.6	961.3	934.5	868.4	758.1	607.2
	-30	957.9	973.4	942.2	865.1	738.5	576.4
	-15	964.2	979.0	944.1	854.6	711.5	545.8
N	0	966.1	982.0	944.8	850.4	701.0	535.9
	15	964.8	981.0	946.4	858.2	714.6	545.6
	30	959.3	975.8	945.8	870.0	744.0	579.1
NE	45	948.6	964.4	937.8	873.0	766.2	615.8
	60	933.6	943.7	918.6	858.7	764.0	629.1
	75	913.1	913.3	882.9	823.1	735.2	613.0
E	90	888.1	869.8	830.4	767.0	679.5	566.2

W	west
NW	north-west
N	north
NE	north-east
E	east

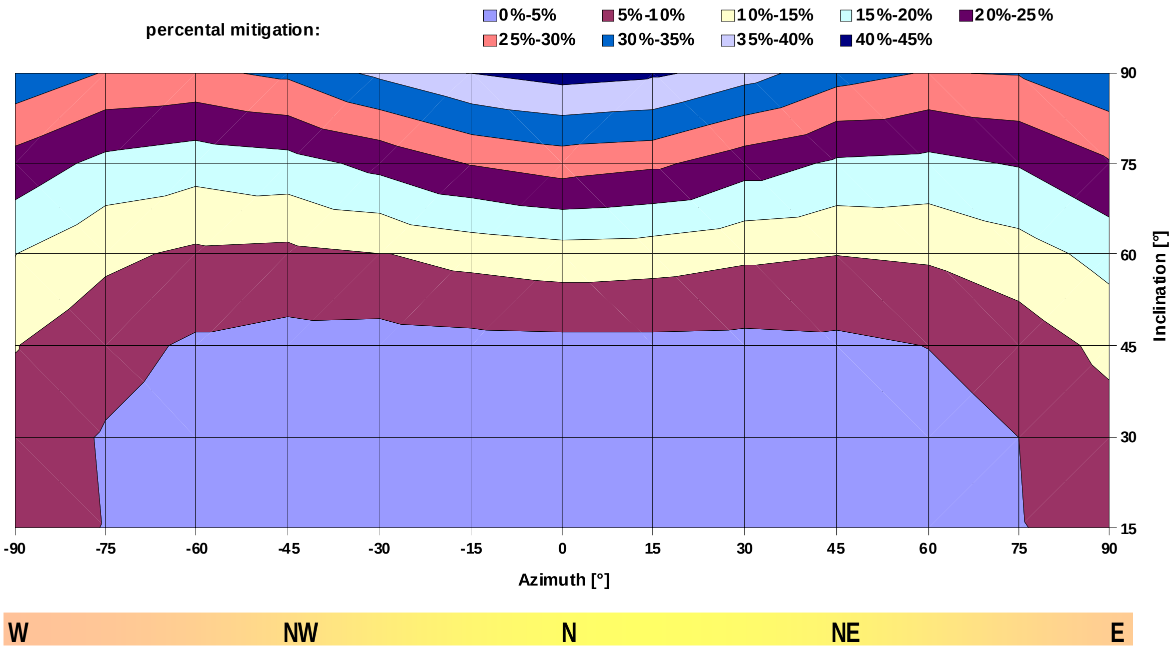


Figure 3: Variations of the annual solar yield in [kWh/m²·a] in **Windhoek** related to different orientations and azimuth angles

Table 3: Variations of the annual solar yield in [kWh/m²·a] in **Windhoek** related to different orientations and azimuth angles. The calculations are based on a solar hot water system with 3m² collector area and a daily hot water consumption of 150 litre.

Azimuth [°]		Inclination [°]					
		15	**30**	**45**	**60**	**75**	**90**
W	**-90**	982.6	972.3	943.6	891.7	808.2	694.9
	-75	999.7	1002.0	981.4	934.7	855.8	739.7
	-60	1013.2	1023.3	1005.9	955.4	870.9	748.9
NW	**-45**	1024.0	1038.6	1017.3	958.9	859.9	723.7
	-30	1031.5	1045.2	1019.5	948.0	826.5	671.8
	-15	1036.1	1049.8	1014.8	928.8	785.2	628.3
N	**0**	1037.9	**1051.0**	1012.1	917.5	764.0	609.8
	15	1036.9	1049.2	1012.0	923.3	777.5	619.5
	30	1033.2	1045.0	1013.7	938.1	817.2	661.9
NE	**45**	1026.3	1036.8	1010.2	945.3	848.2	714.6
	60	1015.8	1022.2	997.6	939.4	854.9	739.7
	75	1000.5	998.5	973.2	916.2	836.9	731.2
E	**90**	982.3	967.4	932.7	874.3	793.7	691.1

W west
NW north-west
N north
NE north-east

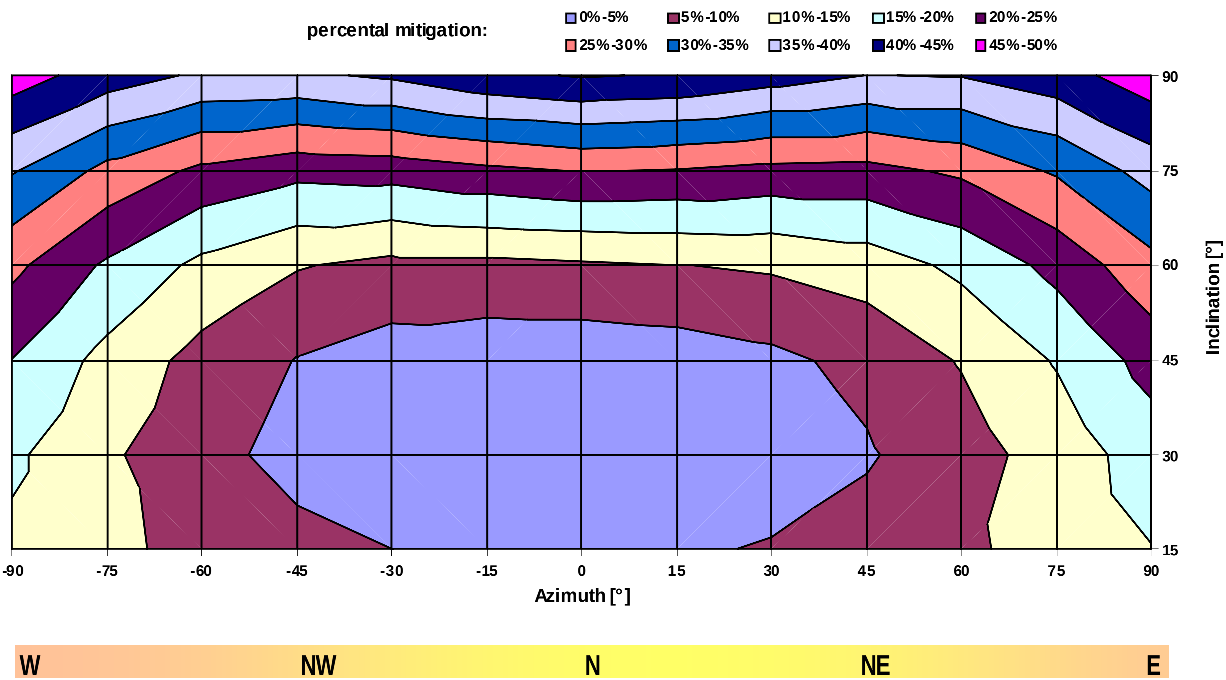


Figure 4: Variations of the annual solar yield in [kWh/m^2·a] in **Cape Town** related to different orientations and azimuth angles

Table 4: Variations of the annual solar yield in [kWh/m^2·a] in **Cape Town** related to different orientations and azimuth angles. The calculations are based on a solar hot water system with 3m^2 collector area and a daily hot water consumption of 150 litre.

Azimuth [°]		**Inclination [°]**					
		15	**30**	**45**	**60**	**75**	**90**
W	**-90**	820.8	802.0	763.6	703.4	616.1	499.5
	-75	848.2	850.7	825.7	770.0	681.5	550.9
	-60	872.1	891.0	875.0	822.0	726.3	579.0
NW	**-45**	891.6	921.5	907.8	855.2	748.3	582.5
	-30	905.8	941.3	928.5	869.7	744.7	563.7
	-15	913.8	951.6	936.3	869.1	726.0	535.1
N	**0**	916.5	953.5	936.4	863.5	714.0	521.2
	15	912.3	947.5	930.3	859.3	718.5	528.4
	30	902.0	933.7	916.5	852.7	730.1	553.2
NE	**45**	886.4	910.6	893.0	834.8	730.4	572.8
	60	865.9	878.8	855.2	799.8	707.4	570.7
	75	840.9	837.0	806.5	748.5	661.7	544.4
E	**90**	812.4	788.3	745.1	681.9	601.2	496.9

W west
NW north-west
N north
NE north-east

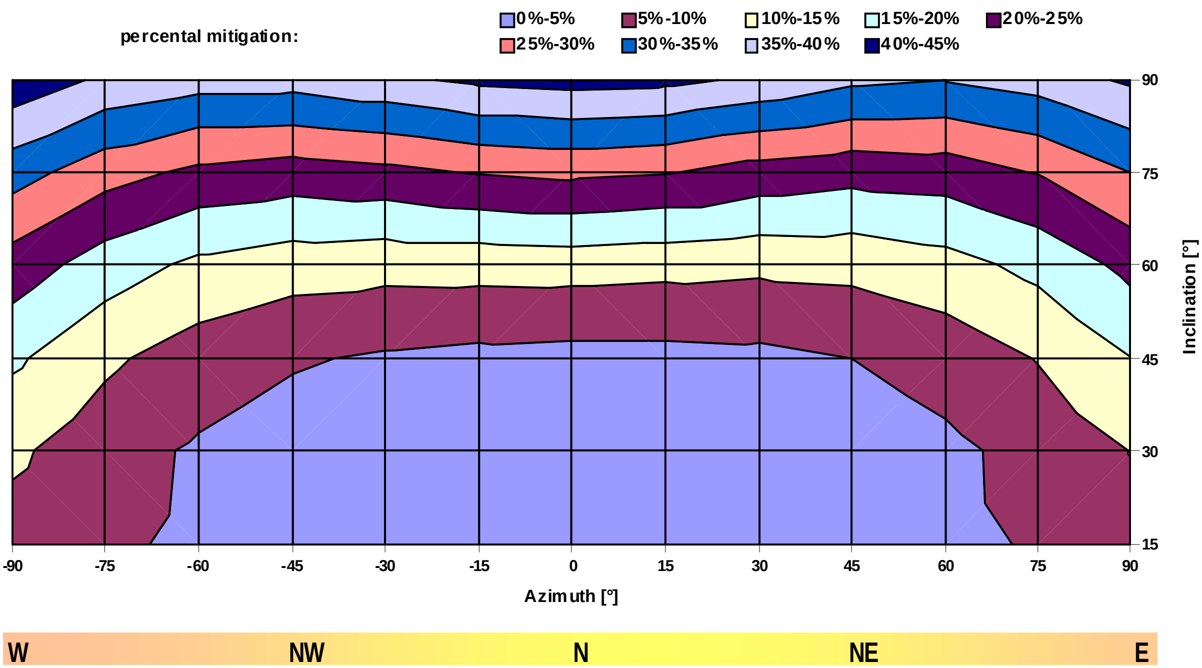


Figure 5: Variations of the annual solar yield in [kWh/m²·a] in **Maputo** related to different orientations and azimuth angles

Table 5: Variations of the annual solar yield in [kWh/m²·a] in **Maputo** related to different orientations and azimuth angles. The calculations are based on a solar hot water system with 3m² collector area and a daily hot water consumption of 150 litre.

Azimuth [°]		Inclination [°]					
		15	**30**	**45**	**60**	**75**	**90**
W	**-90**	826.3	799.2	754.8	691.3	608.4	508.0
	-75	845.1	833.8	798.8	739.2	654.9	546.4
	-60	860.7	858.2	829.5	772.1	683.4	565.2
NW	**-45**	872.9	876.0	847.4	788.2	693.1	565.2
	-30	881.8	887.3	858.4	792.2	685.3	548.0
	-15	887.0	894.6	863.7	790.2	669.4	529.9
N	**0**	889.4	897.30	866.3	789.1	661.8	523.0
	15	888.3	895.9	865.8	793.1	670.0	525.9
	30	883.0	890.8	862.4	798.1	690.5	547.3
NE	**45**	874.9	879.8	852.5	794.5	701.7	572.6
	60	863.2	862.5	833.8	779.4	695.8	580.1
	75	847.9	837.9	805.5	749.8	670.1	565.3
E	**90**	829.6	806.2	764.2	704.6	627.3	531.2

W	west
NW	north-west
N	north
NE	north-east
E	east

Slope angle of tilt

Apart from the effect of the characteristics of the collector itself, the output of the solar system is dependent on the inclination angle of the collector to the sun. The largest yield is obtained when the collector is always orientated perpendicular to the sun. However, the optimal tilt angle for the collectors varies according to the season, as the sun is higher in the sky in summer than in winter. As a general rule, *the optimum angle of tilt is equal to the degree of latitude of the site* . But the minimum angle of the collector should be 15 degree to assist the thermosyphon effect**.** The following table shows optimum tilt angles of different latitudes and seasons.

Table 6: Tilt angle for different latitudes and seasons

Latitude [degree]	**Best collector tilt in:**					
	June	Orientation	**Sept./March**	Orientation	**December**	Orientation
50 N	26.5	S	50	S	73.5	S
40 N	16.5	S	40	S	63.5	S
30 N	6.5	S	30	S	53.5	S
20 N	3.5	N	20	S	43.5	S
15 N	8.5	N	15	S	38.5	S
10 N	13.5	N	10	S	33.5	S
Equator = 0	**23.5**	**N**	**0**	**-**	**23.5**	**S**
10 S	33.5	N	10	N	13.5	S
15 S	38.5	N	15	N	8.5	S
20 S	43.5	N	20	N	3.5	S
30 S	53.5	N	30	N	6.5	N
40 S	63.5	N	40	N	16.5	N
50 S	73.5	N	50	N	26.5	N

Optimum tilt angle – Example 2: Johannesburg, South Africa

Location: Johannesburg, South Africa

Latitude: 26.2 degree South (see table: latitude = 30 degree)

For a north-orientated surface, the energy gain in June is largest for a tilt angle of 53.5°. In December, the most favourable angle would be 6.5° north facing. An angle of 26° is ideal for use throughout the year.

Note: To ensure a good performance of a thermosyphon system a minimum tilt angle of 15° is recommended.

1.7 Dimensioning table for solar hot water systems

The dimensioning indicated in the tables below is to be understood as guidelines for southern African (**Fehler! Verweisquelle konnte nicht gefunden werden.**3) conditions. In order to gain exact information, a calculation based on the system site characteristics in question is recommended. Such calculations can be performed with the help of simulation programs. These give exact predictions of the solar fraction and the system efficiency for the planned system as well as information on the additional energy needed during the rainy season.

Table 7: Dimensioning of domestic hot water solar systems for southern African conditions

Daily hot water demand [litres]	Solar storage capacity [litres]	Collector area* SV [m^2]	Collector area* SC [m^2]
50	50 – 75	1.0 – 1.5	0.9 – 1.3
100	100 – 150	2.0 – 3.0	1.5 – 2.5
200	200 – 300	3.5 – 4.5	3.0 – 4.0
300	300 – 450	4.5 – 6.0	4.0 – 5.0
500	500 - 750	7.5 - 10	6.0 – 8.5
1,000	1,000 – 1,200	14 - 20	11 - 16
2,000	2,000 – 2,500	30 - 40	24 - 32
4,000	4,000 – 5,000	60 - 80	50 – 70
10,000	10,000 – 12,000	140 - 200	110 - 160

*) depending on the required solar fraction

SV ... coating of solar varnish

SC ... selective coating

2 Heat Exchanger

In order to avoid calcification, caused by hard water, and to allow the use of antifreeze in the collector loop a heat exchanger is used between collector and the storage.

The performance of a heat exchanger should be as high as possible and the pressure drop as low as possible. They should be user friendly and of low maintenance.

Heat is generated in the collectors in the primary circuit and a mixture of water and antifreeze is circulating. In the secondary circuit water is circulating (drinking water or water for space heating). The heat should be transferred with a very low difference of temperature to the secondary circuit.

The temperature difference of a heat exchanger describes the difference between the temperature at the entrance of the one circuit and the exit of the other circuit. The lower the temperature difference, the bigger the area of the heat exchanger must be. Usually the temperature difference is about 5K. Lower temperature differences are uneconomic.

The distance covered by the media to transfer the heat (e.g. in a pipe) is called the thermal length.

The circulation in the secondary circuit takes place according to the type of heat exchanger: free convection because of gravity in internal heat exchangers (corded tube heat exchanger, smooth tube heat exchanger) and forced convection in external heat exchangers (plate heat exchangers, cane bundle heat exchangers).

In the following plate heat exchangers and internal heat exchangers are described in detail, as they are used most often.

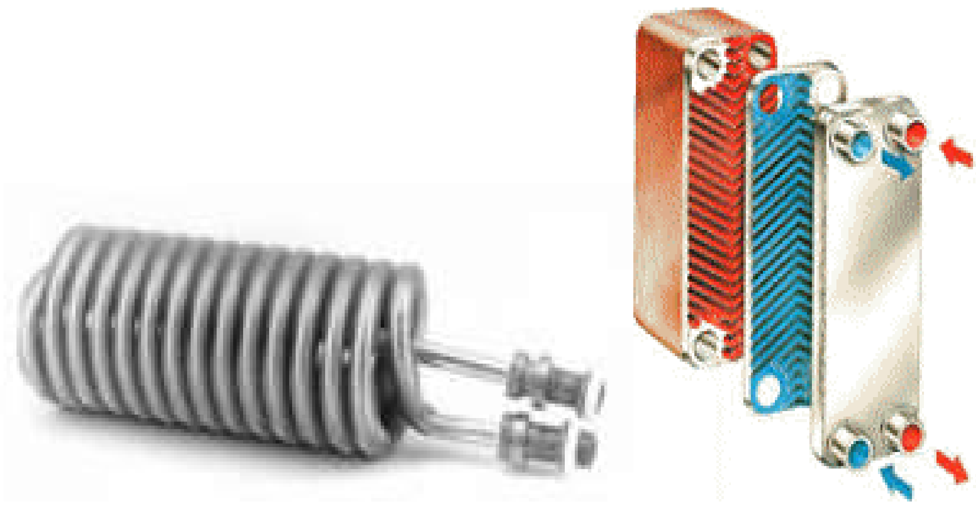


Figure 6: Corded-tube heat exchanger (left), plate heat exchanger (right) Source: 12

2.1 Coil heat exchangers

Coil heat exchangers can be carried out as corded tube heat exchanger or as smooth tube heat exchanger. Typical U-values are between 100 and 500 W/m²K.

The heat exchange power per m² of a smooth tube heat exchanger is higher than that of a corded tube heat exchanger. But in order to reach the same heat exchanging area as the finned tube heat exchanger the length of the pipes must me much longer.

Figure 7: Corded tube heat exchanger (top); smooth tube heat exchanger (bottom)

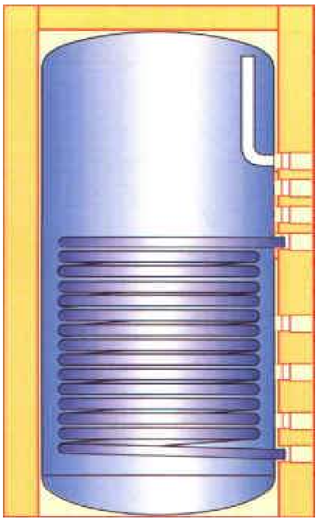


Figure 8: Smooth tube heat exchanger integrated in a domestic hot water storage

Because of its good heat conduction, copper is used to build heat exchangers. The figure above shows a typical application of a coil heat exchanger inside a tank. The advantage of these heat exchangers is the relatively simple construction and a low pressure drop compared to plate heat exchangers. Moreover they are often integrated in the tank by the manufacturer, so there is no additional need for space or installation work.

Internal heat exchangers are available as accessories for a certain heat storage tank. The geometry of the heat exchanger is therefore depending on the dimensions of the heat storage tank. External heat exchangers are available in any size and power regardless of the tank. With external heat exchangers more combinations in the hydraulic scheme of the solar thermal system are possible.

As a rule of thumb an average logarithmic temperature difference of 10 K is good for the dimensioning of internal heat exchangers:

Smooth tube heat exchanger:
approx. 0.2 m² heat exchanger surface per m² collector area

Corded tubes heat exchanger:
approx. 0.3 – 0.4 m² heat exchanger surface per m² collector area

The given numbers represent minimum values!

Deposits of lime
Lime deposits reduce the effective heat transfer area significantly. A 2 mm layer leads to a decrease of 20 % of the heat transfer power, a 5 mm layer to more than 40 %. At a long-term run with hard water at above 60 °C leads to calcination, as shown in the figure below.

Figure 9: Calcification at a heat exchanger (left picture) and at pipes (middle and right picture) (Source: 13)

- **Countermeasures**

Different countermeasures against calcification are:

- The maximum temperature should not exceed 60 °C
- Highly turbulent flow in the heat exchanger
- Pre-treatment of the water

2.2 Plate heat exchanger (external)

Plate heat exchangers are used for solar thermal systems with solar collector areas of 15 m² and more. They are made of parallel plates. In between the plates there is a counter flow of the heat transfer fluids. Due to the special pattern of the plates a turbulent flow is generated. This raises the heat transfer. Plate heat exchangers can be soldered or bolted. With screwed plate heat exchangers the number of the plates can be changed, and it is also possible to exchange single plates. At applications up to 300 kW soldered plate heat exchangers are used because of a number of advantages:

- They are very compact compared with ordinary coil heat exchangers.
- They save about 85 to 90 % in volume and weight.
- Maximum exploitation of the material: the capacity is 25 % higher than the capacity of screwed plate heat exchangers.
- The capacity is 10 times higher compared to the capacity of coil heat exchangers.
- Less use of energy, because of a better heat transfer coefficient and consequently a better temperature difference
- Heat transfer still at a temperature difference of 1 K
- Possibility of high pressures at operation

- **Disadvantage:**

Like for all other external heat exchangers, an additional pump is necessary on the secondary side of the heat exchanger.

3 Calculation of the membrane expansion vessel (MEV)

3.1 Primary fluid in the MEV vessel

The MEV must contain a certain amount of primary fluid at all states of operation of the system. That assures there is always enough fluid in the system.

When taking the system into operation, the pressure in the system (pressure of the fluid) is set slightly higher (approx. 0.5 bar) than the pressure in the MEV. It is important that this adjustment is done as long as the whole system is cold and the pump is off. That guarantees the establishment of the primary fluid in the vessel, which is absolutely necessary.

In the state of stagnation of solar thermal collectors the heat transfer fluid vaporises. The primary fluid in the MEV must be able to cool down the hot fluid that comes from the collector (with temperatures up to 130 °C) to the maximum permissible temperature of the membrane (90 °C). For that reason there must be enough fluid in the expansion vessel already [20].

3.2 Primary air pressure in the MEV

In order to push back the expanded volume into the system, and to make sure not too much fluid enters the expansion vessel a primary pressure is necessary.

If there is too little pressure, a lot of heat transfer fluid enters the expansion vessel at low system temperatures. The consequences would be that at higher temperatures no more fluid could enter the expansion vessel. With closed systems the content of the collector vaporises at stagnation and the expansion vessel must be able to take in the whole volume of the collector. Otherwise the pressure of the system would exceed the pressure that is necessary to release the safety valve, which would lead to a loss of fluid.

It is very important to check the primary pressure when installing the expansion vessel. It is further recommended to have periodical checks every one or two years.

3.3 Design of the solar membrane expansion vessel

In general it must be said that it is better to choose the expansion vessel rather too big than too small!

The results of simulations of expansion vessels are often too optimistic. Certain processes in the solar thermal system, like the stagnation, have not (or not adequately) been taken into account. Please see in the following calculation method (that considers the influence of the stagnation) to the state of the art.

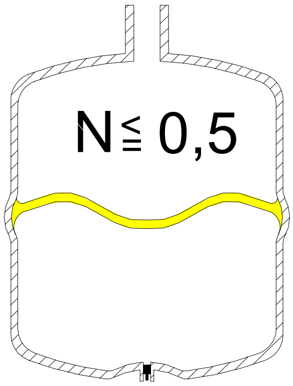


Figure 10: Actual use of the MEV (20)

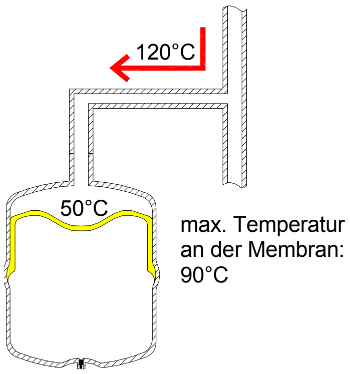


Figure 11: Primary fluid in the MEV (21)

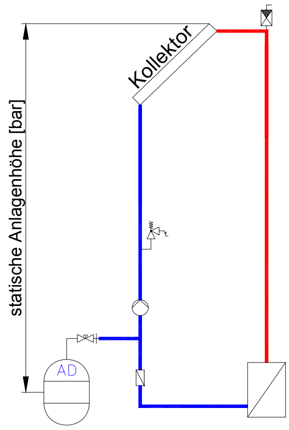


Figure 12:

Minimal primary pressure in the MEV (20)

The following important parameters must be well-known for simulation and installation:

The utilization factor is given by the manufacturer. It specifies the volume of the expansion vessel that can actually be used without expanding the membrane excessively. This would lead to damage on the membrane and to a lower life time of the expansion vessel. Usually the utilization factor is less than 0.5

The primary pressure in the expansion vessel should at least correspond to the static hydraulic height of the system. Because of the primary pressure, the pressure in the system is also high enough in the upper parts of the system. It also prevents air from coming into the system when the heat transfer fluid cools down. After aerating the systems several times there must be enough fluid left. The primary fluid in the expansion vessel takes care of this. Additionally, the primary fluid must protect the membrane against high temperatures at stagnation.

The nominal volume V_N of the expansion vessel (see equation) is calculated in the well known way from the heat expansion of the total content of the heat exchanging fluid V_G*n, the primary fluid V_V, the volume of the vapour V_D and the efficiency N. Compared to previous calculations a bigger volume of the vapour has to be taken into account. Corresponding to the given details above the volume of all pipes and components reached by the vapour has to be calculated.

Up to now the efficiency has only been calculated from the pressure of the system P_e and the primary pressure of the expansion vessel P_0. In the new method of calculation the difference of height H_{diff} between the expansion vessel and the safety valve is considered (equation 4). These components may be installed in different storeys of the building and lead to the pressure difference P_{diff}. The rise of temperature of the gas filling during operation is also considered (differences of 30 K have been measured). This leads to the quotient 0.9. These changes result from the application of the general gas law to the conditions at issue:

$$V_N > \frac{V_G \cdot n + V_V + V_D}{N}$$ (equation 1)

$$n = \frac{\rho_{cold}}{\rho_{hot}} - 1 \approx \quad (0.09)$$ (equation 2)

$$N = \frac{P_e + P_{diff} + 1 - \frac{(P_0 + 1)}{0.9}}{P_e + P_{diff} + 1}$$ (equation 3)

$$P_{diff} = \frac{-H_{diff} \cdot \rho_{cold} \cdot 9.81}{100{,}000}$$ (equation 4)

Hereby means:

V_N	nominal volume of the expansion vessel	litre
V_G	total volume of the heat exchanging fluid	litre
V_V	primary fluid in the MEV litre	
V_D	maximum volume of the vapour	litre
n	coefficient of expansion (~ 0.09 for expansion at ~120 °C for 40 % propylene glycol)	
N	Utilization factor of the expansion vessel, according to manufacturer ≤ 0,5	
ρ	density of heat transfer fluid	kg/m³
P_e	pressure of system at safety valve = nominal pressure safety valve – 20 %	bar
P_0	primary pressure [bar]. The factor 0.9 in $(P_0+1)/0.9$ stands for a change of temperature in the gas containing space because of the hot fluid	
H_{diff}	difference of height between the expansion vessel and the Safety valve	
H_{diff}	= height of expansion vessel – height of safety valve	m
P_{diff}	difference of pressure according to H_{diff}	bar

As mentioned above, the primary fluid in the expansion vessel must be able to cool down the hot heat exchange fluid coming from the collector. The maximum permissible temperature in the expansion vessel according to the manufacturer is 90 °C. The dimensioning of the minimum of primary fluid in the expansion vessel V_V is shown in equation 5:

maximum permissible temperature in expansion vessel T_{max} = 90 °C,

average temperature in the primary circuit 90 °C,

origin temperature of the primary fluid T_V = 50 °C (according to measurements), In the worst case the expansion vessel must be able to take in the whole volume of the collector V_K at a temperature of T_K = 130 °C.

$$V_V \geq V_K \cdot \frac{T_K - T_{max}}{T_{max} - T_V}$$

(equation 5)

V_V	primary fluid	litre
V_K	volume inside the collector	litre
T_K	temperature of the fluid at entering the expansion vessel	°C
T_{max}	maximum permissible temperature in expansion vessel	°C

From this assumption it follows that the volume of the primary fluid must be equivalent to the volume of the collector.

Example of calculation:

Collector area:	10 m² (collector that empties well)
Flow pipe V_L:	15 m Cu pipe 18x1
Return pipe V_L:	15 m Cu pipe 18x1
Safety valve:	6 bar
Pressure of the system:	2.5 bar
Primary pressure in the expansion vessel:	2.0 bar

We are looking for the volume of the expansion vessel [litre]

A) Formula for calculation

$$V_N > \frac{V_G \cdot n + V_V + V_D}{N}$$

MEV	nominal volume V_N	litre
V_D	maximum vapour volume	litre
V_G	total volume of the heat transfer fluid	litre
V_V	primary fluid	litre
n	coefficient of expansion of the heat transfer fluid	

B) Calculation of the MEV efficiency:

$$N = \frac{P_e + P_{diff} + 1 - \frac{(P_0 + 1)}{0,9}}{P_e + P_{diff} + 1}$$

N	MEV efficiency	
P_e	nominal pressure of safety valve	bar
P_0	primary pressure	bar

$$P_{diff} = \frac{-H_{diff} \cdot \rho_{cold} \cdot 9.81}{100,000}$$

P_{diff}	pressure difference	bar	
H_{diff}	$H_{MEV} – H_{SV}$	m	
r	density of the heat transfer fluid	kg/m³	~1051 kg/m³

$$P_{diff} = \frac{0.5 \cdot 1051 \cdot 9.81}{100,000} = 0.052 bar$$

P_e = nominal pressure of safety valve – tolerance of respond (20 %)

P_e = 6 bar – 20 % = 4.8 bar

Pressure difference P_{diff} = 0.052 bar

Nominal pressure of safety valve P_e = 4.8 bar

P_o = 2.0 bar

$$N = \frac{P_e + P_{diff} + 1 - \frac{(P_0 + 1)}{0.9}}{P_e + P_{diff} + 1} = \frac{4.8 + 0.052 + 1 - \frac{(2.0 + 1)}{0.9}}{4.8 + 0.052 + 1} = 0.43$$

C) Calculation of the volume of the heat transfer fluid:

$V_G = V_{pipe} + V_{coll} + V_{heat\ exchanger}$ litre

Factor of expansion n

$$n = \frac{\rho_{cold}}{\rho_{hot}} - 1 \approx 0.09$$

$$V_G = \frac{0.16^2 \cdot \pi}{4} \cdot 300 + 4.5 + 2.0 = 12.5 \text{ litre}$$

Calculation of the primary fluid V_V:

The volume of the primary fluid is more or less equivalent to the volume of the collector.

->V_V = V_{coll} = 4.5 litre

D) Calculation of the volume of vapour V_D:

V_D = V_{coll} + $V_{pipe\text{-}vapor}$ litre

V_{coll} = 4.5 litre

Calculation of the volume of vapour in the pipes

Maximum vapour power= 10 m² * 50 W/m² = 500 W

Calculation of the reach of the vapour in the solar pipes $V_{pipe\text{-}vapour}$ (calculation through the thermal power loss of the pipes):

thermal power loss of the pipe: 25 W/m

(reach of vapour in the pipe) = (max. vapour power)/(thermal power loss of the pipe per meter of pipe)

(reach of vapour in the pipe) = 500/25 = 20 meter 16 mm Cu pipe

V_D = 4.5 + 4.0 = 8.5 litre

$$V_{pipe-vapour} = \frac{0,16^2 \cdot \pi}{4} \cdot 200 = 4,0 \text{ litre}$$

E) Calculation of the volume of the expansion vessel:

$$V_N > \frac{V_G \cdot n + V_V + V_D}{N} = \frac{12.5 \cdot 0{,}09 + 4{,}5 + 8{,}5}{0{,}43} = 32{,}8\,litre$$

Selection of the expansion vessel -> 35 litre

3.4 Installation

In principle the expansion vessel should be installed in a hanging way. The standing mounting leads to the following effect:

If hot water streams by the expansion vessel it also enters the expansion vessel, because the density of hot water is lower than the density of the cold water inside the vessel (compare figure 5, right).

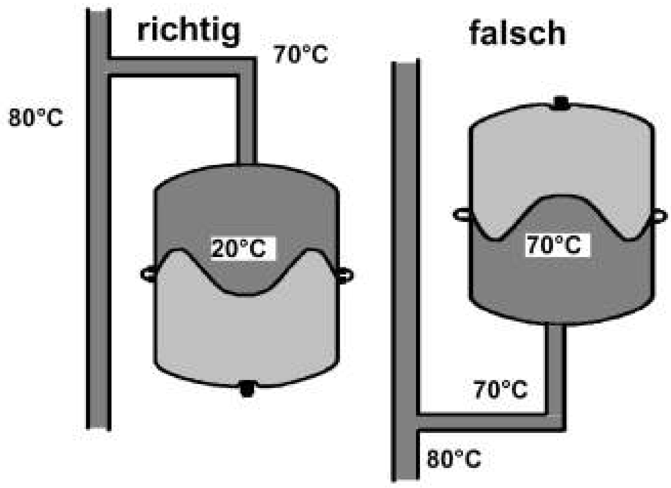


Figure 13: Correct and wrong installation of the MEV (Source:20)

Usually the expansion vessel is not insulated. Therefore it looses a lot of heat. On the other side when bringing the system into operation hot fluid from the (stagnating) collector could enter the expansion vessel. The membrane is not able to stand high temperatures and will be destroyed in the long run. Therefore the correct installation is in a hanging way, and the hot water will always stream by the expansion vessel.

The hanging installation also allows the expansion vessel to aerate automatically: Should there be air in the vessel, this can leave the vessel by rising in the pipes by itself and leave the system via the deaerator. Additionally no more air can enter the suspended vessel.

The expansion vessel is to be mounted without the possibility to lock it from the system. Nevertheless it is necessary to install lockable fittings in order to maintain the system. Those fittings must be protected against inadvertent isolation of the pressure vessel by the use of a lockable stop valve.

1 Mozambique

1.1 Reference climate: Maputo

- Reference system: thermosiphon system

Latitude	-25.9	°
Longitude	-32.6	°
Total Annual Global Radiation	1,805.4	kWh/m²·a
Share of diffuse Radiation	48.5	%
Mean Outside Temperature	23.6	°C
Lowest Outside Temperature	11.2	°C

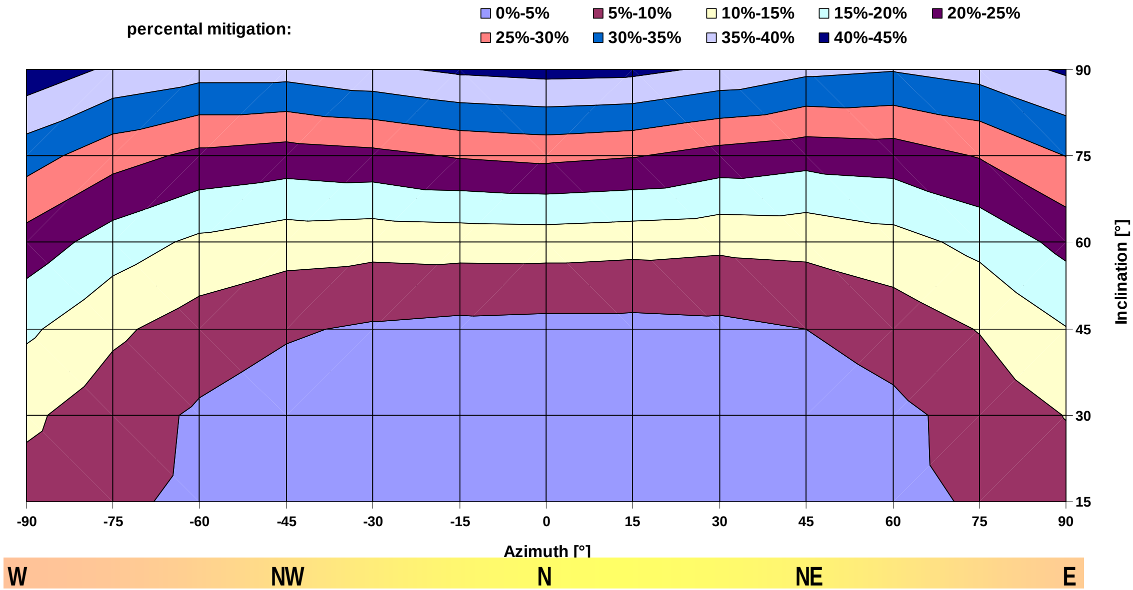


Figure 1.1: Variations of the annual solar yield in [kWh/m²·a] in Maputo related to different orientations and azimuth angles

Table 1.1: Variations of the annual solar yield in [kWh/m²·a] in Maputo related to different orientations and azimuth angles

Azimuth [°]		Inclination [°]					
		15	**30**	**45**	**60**	**75**	**90**
W	**-90**	826.3	799.2	754.8	691.3	608.4	508.0
	-75	845.1	833.8	798.8	739.2	654.9	546.4
	-60	860.7	858.2	829.5	772.1	683.4	565.2
NW	**-45**	872.9	876.0	847.4	788.2	693.1	565.2
	-30	881.8	887.3	858.4	792.2	685.3	548.0
	-15	887.0	894.6	863.7	790.2	669.4	529.9
N	**0**	889.4	897.30	866.3	789.1	661.8	523.0
	15	888.3	895.9	865.8	793.1	670.0	525.9
	30	883.0	890.8	862.4	798.1	690.5	547.3
NE	**45**	874.9	879.8	852.5	794.5	701.7	572.6
	60	863.2	862.5	833.8	779.4	695.8	580.1
	75	847.9	837.9	805.5	749.8	670.1	565.3
E	**90**	829.6	806.2	764.2	704.6	627.3	531.2

W west
NW north-west
N north
NE north-east
E east

2 Namibia

2.1 Reference climate: Windhoek

- Reference system: thermosiphon system

Latitude	-22.6	°
Longitude	-17.1	°
Total Annual Global Radiation	2.363,0	kWh/m²·a
Share of diffuse Radiation	47.4	%
Mean Outside Temperature	21.0	°C
Lowest Outside Temperature	1.9	°C

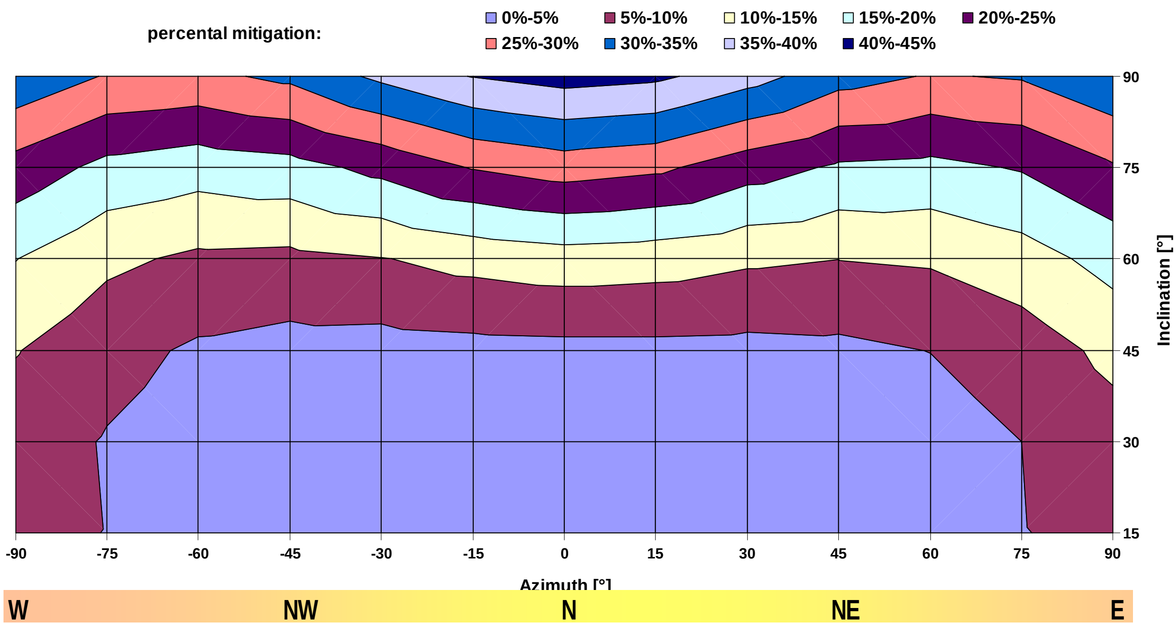


Figure 2.1: Variations of the annual solar yield in [kWh/m²·a] in Windhoek related to different orientations and azimuth angles

Table 2.1: Variations of the annual solar yield in [kWh/m²·a] in Windhoek related to different orientations and azimuth angles

Azimuth [°]		Inclination [°]					
		15	**30**	**45**	**60**	**75**	**90**
W	**-90**	982.6	972.3	943.6	891.7	808.2	694.9
	-75	999.7	1002.0	981.4	934.7	855.8	739.7
	-60	1013.2	1023.3	1005.9	955.4	870.9	748.9
NW	**-45**	1024.0	1038.6	1017.3	958.9	859.9	723.7
	-30	1031.5	1045.2	1019.5	948.0	826.5	671.8
	-15	1036.1	1049.8	1014.8	928.8	785.2	628.3
N	**0**	1037.9	**1051.0**	1012.1	917.5	764.0	609.8
	15	1036.9	1049.2	1012.0	923.3	777.5	619.5
	30	1033.2	1045.0	1013.7	938.1	817.2	661.9
NE	**45**	1026.3	1036.8	1010.2	945.3	848.2	714.6
	60	1015.8	1022.2	997.6	939.4	854.9	739.7
	75	1000.5	998.5	973.2	916.2	836.9	731.2
E	**90**	982.3	967.4	932.7	874.3	793.7	691.1

W west
NW north-west
N north
NE north-east

3 South Africa

3.1 Reference climate: Cape Town

- Reference system: thermosiphon system

Latitude	-33.9	°
Longitude	-18.5	°
Total Annual Global Radiation	1,952.9	kWh/m²·a
Share of diffuse Radiation	39.1	%
Mean Outside Temperature	16.9	°C
Lowest Outside Temperature	3.4	°C

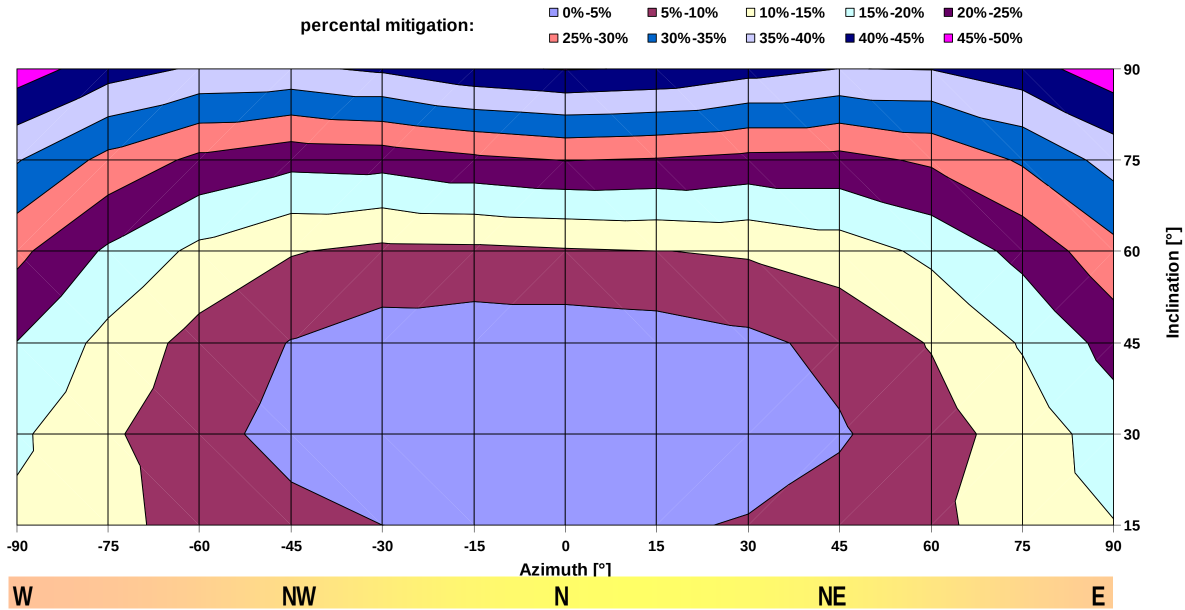


Figure 3.1: Variations of the annual solar yield in [kWh/m²·a] in Cape Town related to different orientations and azimuth angles

Table 3.1: Variations of the annual solar yield in [kWh/m²·a] in Cape Town related to different orientations and azimuth angles

Azimuth [°]		Inclination [°]					
		15	30	45	60	75	90
W	-90	820.8	802.0	763.6	703.4	616.1	499.5
	-75	848.2	850.7	825.7	770.0	681.5	550.9
	-60	872.1	891.0	875.0	822.0	726.3	579.0
NW	-45	891.6	921.5	907.8	855.2	748.3	582.5
	-30	905.8	941.3	928.5	869.7	744.7	563.7
	-15	913.8	951.6	936.3	869.1	726.0	535.1
N	0	916.5	953.5	936.4	863.5	714.0	521.2
	15	912.3	947.5	930.3	859.3	718.5	528.4
	30	902.0	933.7	916.5	852.7	730.1	553.2
NE	45	886.4	910.6	893.0	834.8	730.4	572.8
	60	865.9	878.8	855.2	799.8	707.4	570.7
	75	840.9	837.0	806.5	748.5	661.7	544.4
E	90	812.4	788.3	745.1	681.9	601.2	496.9

W west
NW north-west
N north
NE north-east
E east

3.2 Reference climate: Johannesburg

- Reference system: thermosiphon system

Latitude	-26.2	°
Longitude	-28.0	°
Total Annual Global Radiation	2.075,1	kWh/m²·a
Share of diffuse Radiation	47.2	%
Mean Outside Temperature	15.6	°C
Lowest Outside Temperature	-1.5	°C

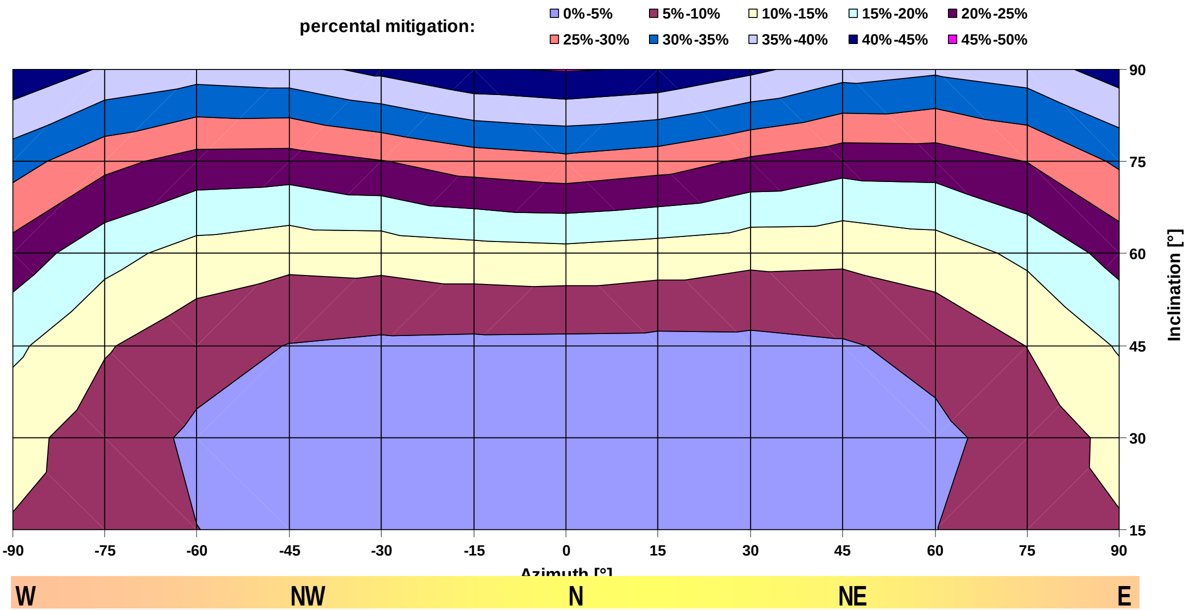


Figure 3.2: Variations of the annual solar yield in [kWh/m²·a] in Johannesburg related to different orientations and azimuth angles

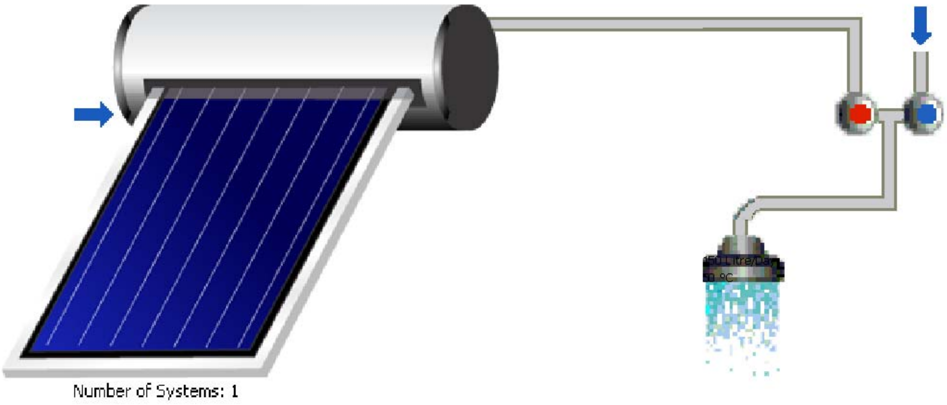
Table 3.2: Variations of the annual solar yield in [kWh/m²·a] in Johannesburg related to different orientations and azimuth angles

Azimuth [°]		Inclination [°]					
		15	**30**	**45**	**60**	**75**	**90**
W	**-90**	887.9	867.0	824.5	757.1	665.9	549.7
	-75	912.3	909.6	879.6	817.0	722.3	595.1
	-60	932.3	940.9	914.7	854.0	754.9	614.7
NW	**-45**	947.6	961.3	934.5	868.4	758.1	607.2
	-30	957.9	973.4	942.2	865.1	738.5	576.4
	-15	964.2	979.0	944.1	854.6	711.5	545.8
N	**0**	966.1	**982.0**	944.8	850.4	701.0	535.9
	15	964.8	981.0	946.4	858.2	714.6	545.6
	30	959.3	975.8	945.8	870.0	744.0	579.1
NE	**45**	948.6	964.4	937.8	873.0	766.2	615.8
	60	933.6	943.7	918.6	858.7	764.0	629.1
	75	913.1	913.3	882.9	823.1	735.2	613.0
E	**90**	888.1	869.8	830.4	767.0	679.5	566.2

W west
NW north-west
N north
NE north-east
E east

4 Attachments

4.1 T-Sol Calculation Maputo



Installed Collector Power:	2,10 kW	
Installed Gross Solar Surface Area:	3 m²	
Collector Surface Area Irradiation (Active Surface):	5,73 MWh	1.910,50 kWh/m²
Energy Produced by Collectors:	3.026,15 kWh	1.008,72 kWh/m²
Energy Produced by Collector Loop:	2.691,89 kWh	897,30 kWh/m²
DHW Heating Energy Supply:	2061,21 kWh	
Solar Contribution to DHW:	2691,89 kWh	
Electricity Savings:		**3.451,1 kWh**
CO2 Emissions Avoided:		**2.298,46 kg**
DHW Solar Fraction:		**100,0 %**
Fractional Energy Saving (EN 12976):		**97,9 %**
System Efficiency:		**47,0 %**

Basic Data

Climate File

Location:	Maputo
Climate Data Record:	"MAPUTO MZ"
Total Annual Global Radiation:	1805,42 kWh
Latitude:	-25,94 °
Longitude:	-32,56 °

Domestic Hot Water

Average Daily Consumption:	150 l
Desired Temperature:	50 °C
Load Profile:	Detached House (evening max)
Cold Water Temperature:	February:18 °C / August:15 °C
Circulation:	No

System

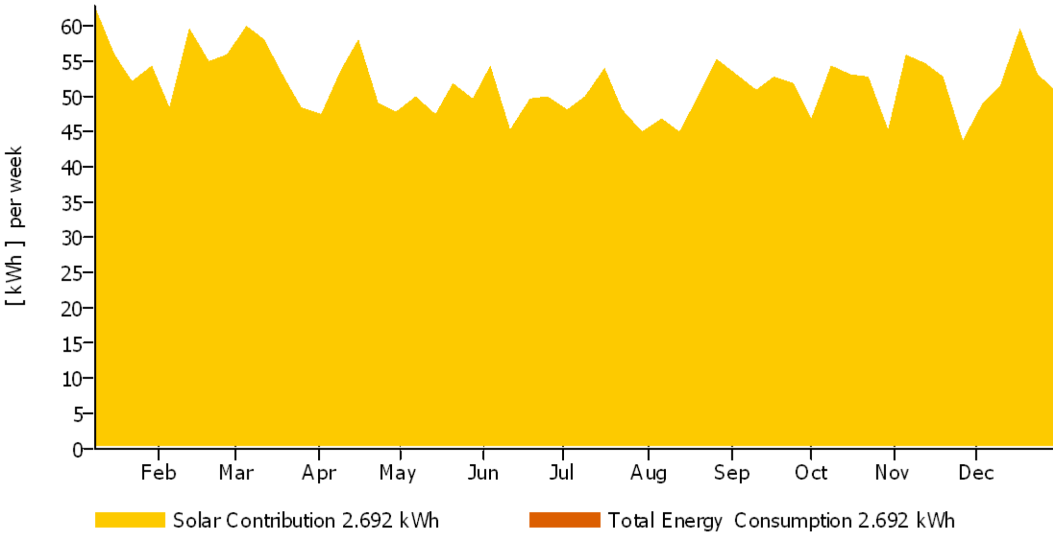
Thermosyphon System

Collector Area (Active Solar Surface):	3 m²
Type:	Standard Flat-Plate Collector
Tilt Angle:	30 °
Azimuth:	0 °
Storage Tank Volume:	200 l

Legend

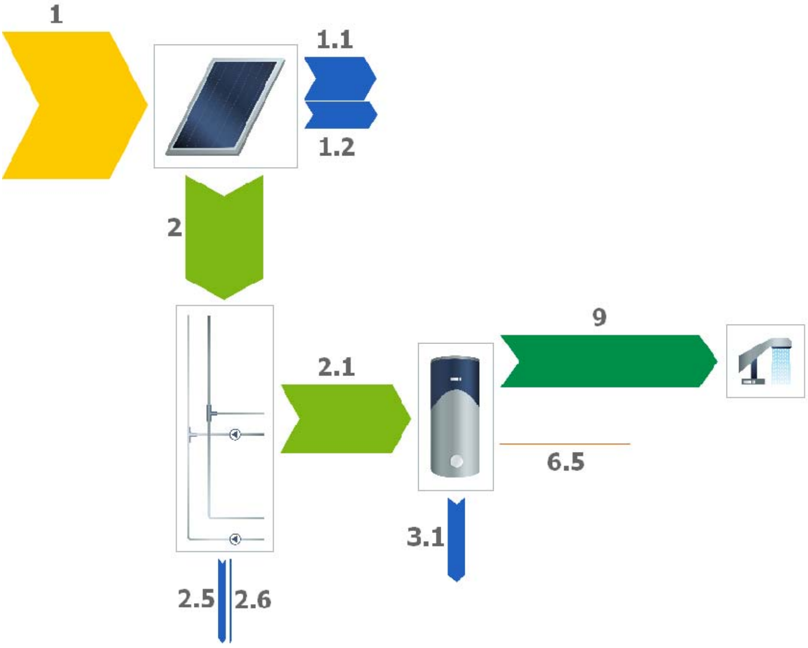
Original T*SOL Database
CERTIFIED With Test Report
Solar Keymark

Solar Energy Consumption as Percentage of Total Consumption



These calculations were carried out by T*SOL Expert 4.5 - the Simulation Programme for Solar Thermal Heating Systems. The results are determined by a mathematical model calculation with variable time steps of up to 6 minutes. Actual yields can deviate from these values due to

Energy Balance Schematic



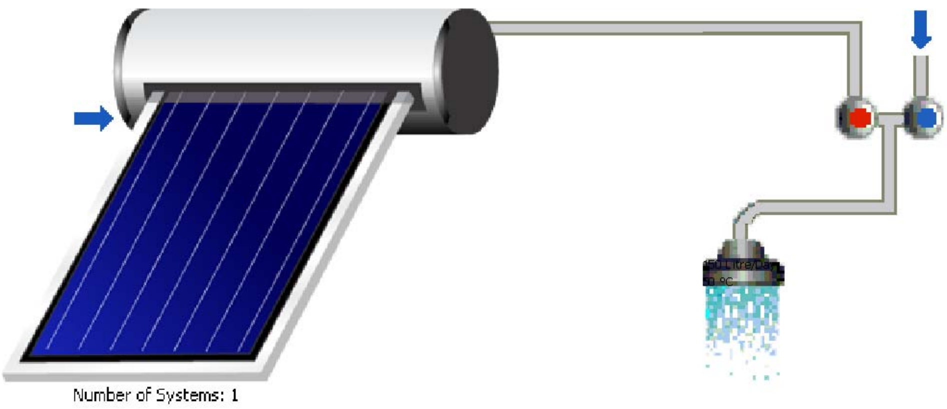
Legend

1	Collector Surface Area Irradiation (Active Surface)	5.732 kWh
1.1	Optical Collector Losses	1.667 kWh
1.2	Thermal Collector Losses	1.039 kWh
2	Energy from Collector Array	3.026 kWh
2.1	Solar Energy to Storage Tank	2.692 kWh
2.5	Internal Piping Losses	299 kWh
2.6	External Piping Losses	35 kWh
3.1	Tank Losses	631 kWh
6.5	Heating Element	0 kWh
9	DHW Energy from Tank	2.061 kWh

Glossary

1 Collector Surface Area Irradiation (Active Surface)
Energy Irradiated onto Tilted Collector Area (Active Solar Surface)
1.1 Optical Collector Losses
Reflection and Other Losses
1.2 Thermal Collector Losses
Heat Conduction and Other Losses
2 Energy from Collector Array
Energy Output at Collector Array Outlet (i.e. Before the Piping)
2.1 Solar Energy to Storage Tank
Energy from Collector Loop to Storage Tank (Minus Piping Losses)
2.5 Internal Piping Losses
Internal Piping Losses
2.6 External Piping Losses
External Piping Losses
3.1 Tank Losses
Heat Losses via Surface Area
6.5 Heating Element
Energy from Heating Element
9 DHW Energy from Tank
Heat for DHW Appliances from Tank (Exluding Circulation)

4.2 T-Sol Calculation Windhoek



Installed Collector Power:	2,10 kW	
Installed Gross Solar Surface Area:	3 m²	
Collector Surface Area Irradiation (Active Surface):	7,44 MWh	2.479,78 kWh/m²
Energy Produced by Collectors:	3,60 MWh	1.198,64 kWh/m²
Energy Produced by Collector Loop:	3.153,12 kWh	1.051,04 kWh/m²
DHW Heating Energy Supply:	2106,68 kWh	
Solar Contribution to DHW:	3153,12 kWh	
Electricity Savings:		**4.042,5 kWh**
CO2 Emissions Avoided:		**2.692,28 kg**
DHW Solar Fraction:		**100,0 %**
Fractional Energy Saving (EN 12976):		**99,7 %**
System Efficiency:		**42,4 %**

Basic Data

Climate File

Location:	Windhoek
Climate Data Record:	"WINDHOEK WA"
Total Annual Global Radiation:	2362,99 kWh
Latitude:	-22,57 °
Longitude:	-17,1 °

Domestic Hot Water

Average Daily Consumption:	150 l
Desired Temperature:	50 °C
Load Profile:	Detached House (evening max)
Cold Water Temperature:	February:18 °C / August:15 °C
Circulation:	No

System

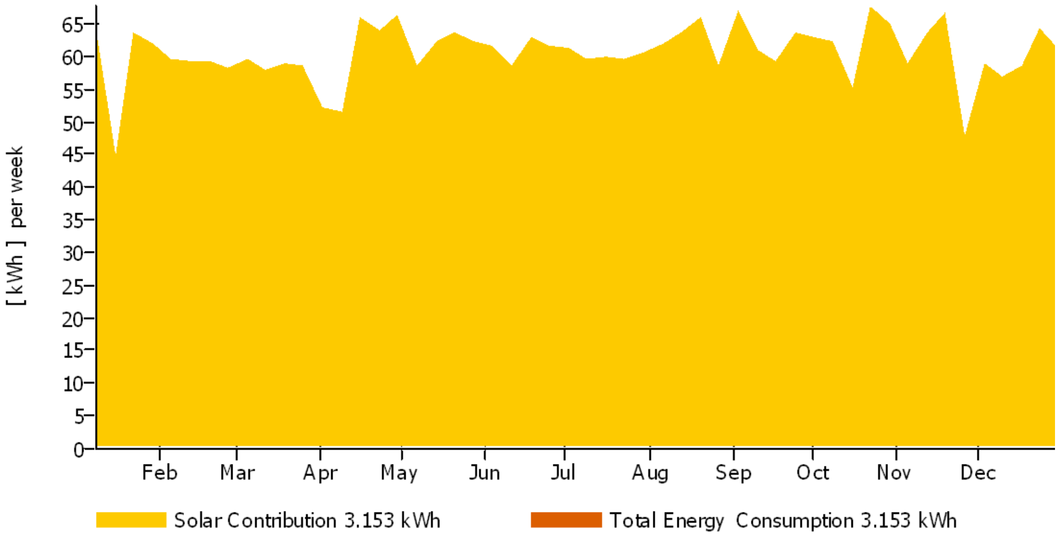
Thermosyphon System

Collector Area (Active Solar Surface):	3 m²
Type:	Standard Flat-Plate Collector
Tilt Angle:	30 °
Azimuth:	0 °
Storage Tank Volume:	200 l

Legend

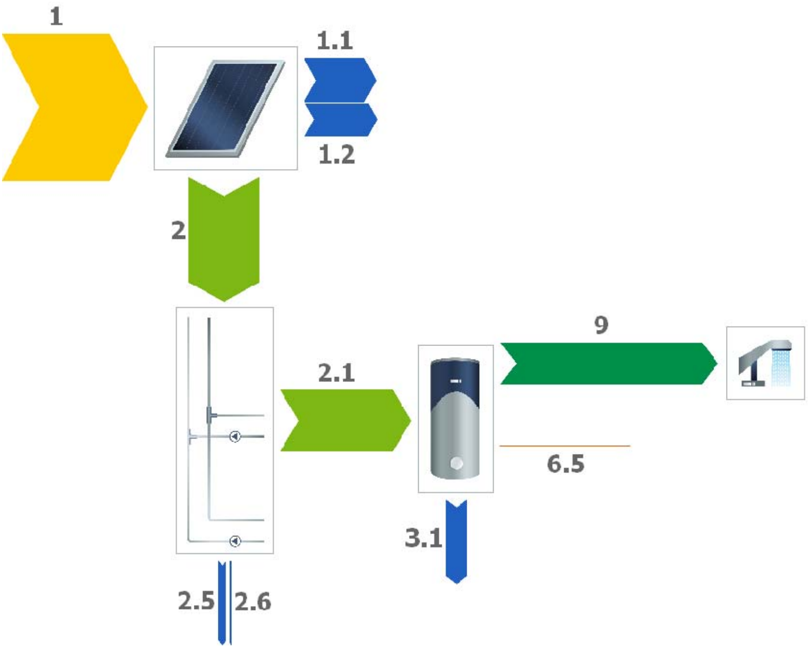
Original T*SOL Database
CERTIFIED With Test Report
Solar Keymark

Solar Energy Consumption as Percentage of Total Consumption



These calculations were carried out by T*SOL Expert 4.5 - the Simulation Programme for Solar Thermal Heating Systems. The results are determined by a mathematical model calculation with variable time steps of up to 6 minutes. Actual yields can deviate from these values due to

Energy Balance Schematic



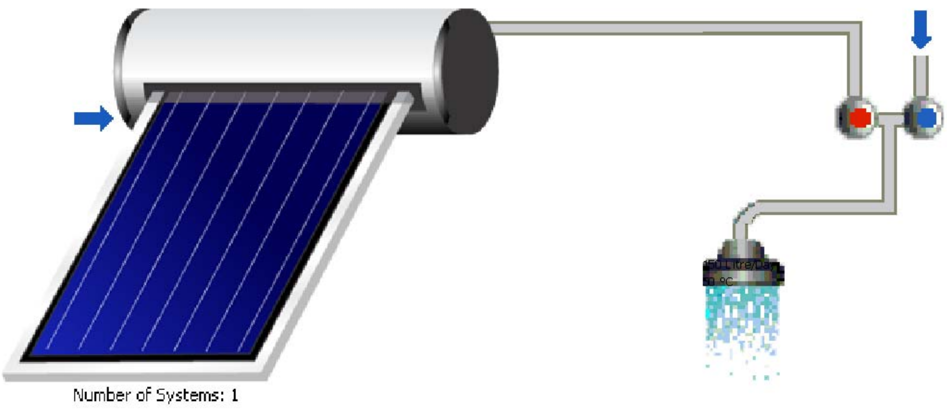
Legend

1	Collector Surface Area Irradiation (Active Surface)	7.439 kWh
1.1	Optical Collector Losses	2.207 kWh
1.2	Thermal Collector Losses	1.636 kWh
2	Energy from Collector Array	3.596 kWh
2.1	Solar Energy to Storage Tank	3.153 kWh
2.5	Internal Piping Losses	389 kWh
2.6	External Piping Losses	54 kWh
3.1	Tank Losses	1.049 kWh
6.5	Heating Element	0 kWh
9	DHW Energy from Tank	2.107 kWh

Glossary

1 Collector Surface Area Irradiation (Active Surface)
Energy Irradiated onto Tilted Collector Area (Active Solar Surface)
1.1 Optical Collector Losses
Reflection and Other Losses
1.2 Thermal Collector Losses
Heat Conduction and Other Losses
2 Energy from Collector Array
Energy Output at Collector Array Outlet (i.e. Before the Piping)
2.1 Solar Energy to Storage Tank
Energy from Collector Loop to Storage Tank (Minus Piping Losses)
2.5 Internal Piping Losses
Internal Piping Losses
2.6 External Piping Losses
External Piping Losses
3.1 Tank Losses
Heat Losses via Surface Area
6.5 Heating Element
Energy from Heating Element
9 DHW Energy from Tank
Heat for DHW Appliances from Tank (Exluding Circulation)

4.3 T-Sol Calculation Cape Town



Installed Collector Power:	2,10 kW	
Installed Gross Solar Surface Area:	3 m²	
Collector Surface Area Irradiation (Active Surface):	6,41 MWh	2.135,14 kWh/m²
Energy Produced by Collectors:	3,19 MWh	1.062,63 kWh/m²
Energy Produced by Collector Loop:	2.860,62 kWh	953,54 kWh/m²
DHW Heating Energy Requirement:	2114,93 kWh	
DHW Heating Energy Supply:	2010,52 kWh	
Solar Contribution to DHW:	2860,62 kWh	
Electricity Savings:		**3.667,5 kWh**
CO2 Emissions Avoided:		**2.442,53 kg**
DHW Solar Fraction:		**100,0 %**
Fractional Energy Saving (EN 12976):		**95,9 %**
System Efficiency:		**44,7 %**

Basic Data

Climate File

Location:	Cape Town
Climate Data Record:	"CAPE TOWN"
Total Annual Global Radiation:	1952,95 kWh
Latitude:	-33,93 °
Longitude:	-18,47 °

Domestic Hot Water

Average Daily Consumption:	150 l
Desired Temperature:	50 °C
Load Profile:	Detached House (evening max)
Cold Water Temperature:	February:18 °C / August:15 °C
Circulation:	No

System

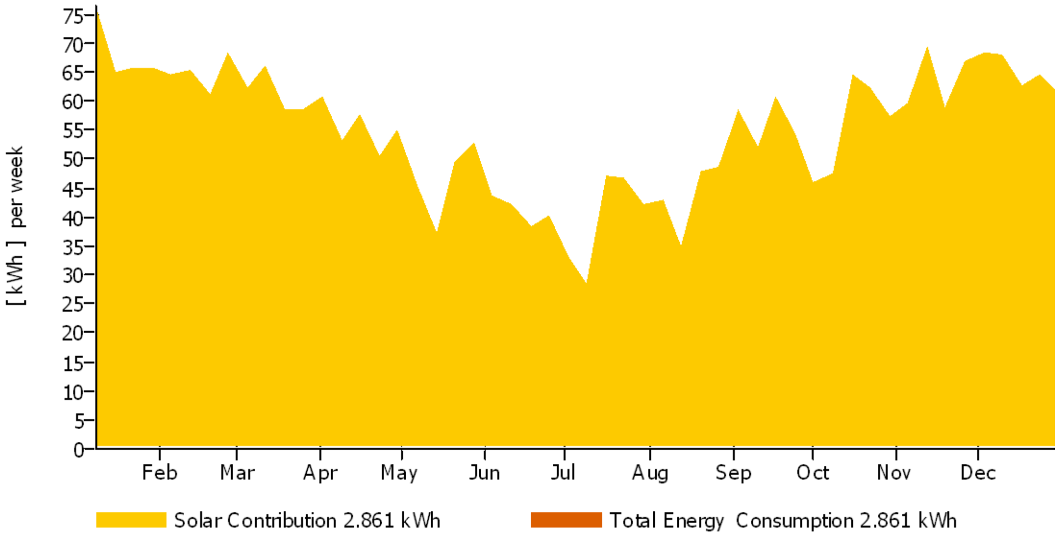
Thermosyphon System

Collector Area (Active Solar Surface):	3 m²
Type:	Standard Flat-Plate Collector
Tilt Angle:	30 °
Azimuth:	0 °
Storage Tank Volume:	200 l

Legend

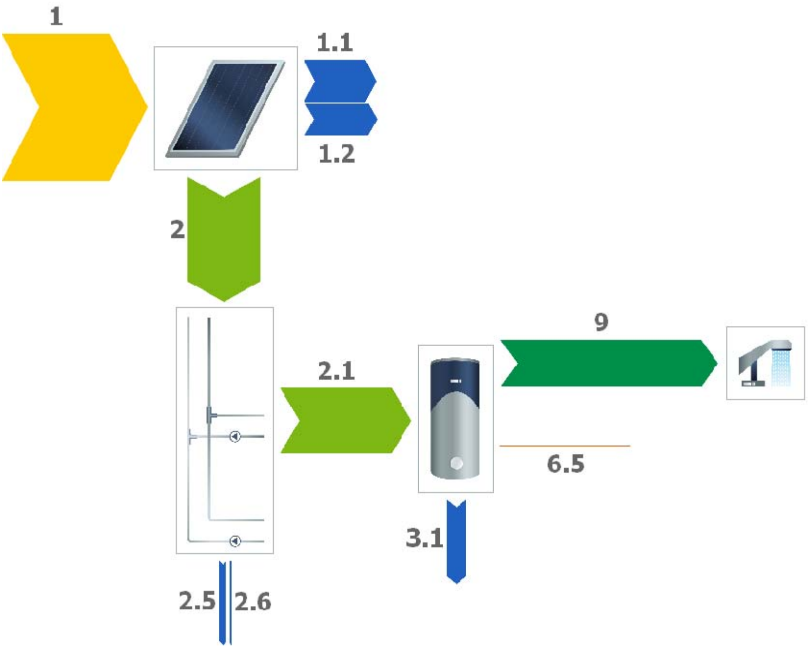
Original T*SOL Database
CERTIFIED With Test Report
Solar Keymark

Solar Energy Consumption as Percentage of Total Consumption



These calculations were carried out by T*SOL Expert 4.5 - the Simulation Programme for Solar Thermal Heating Systems. The results are determined by a mathematical model calculation with variable time steps of up to 6 minutes. Actual yields can deviate from these values due to

Energy Balance Schematic



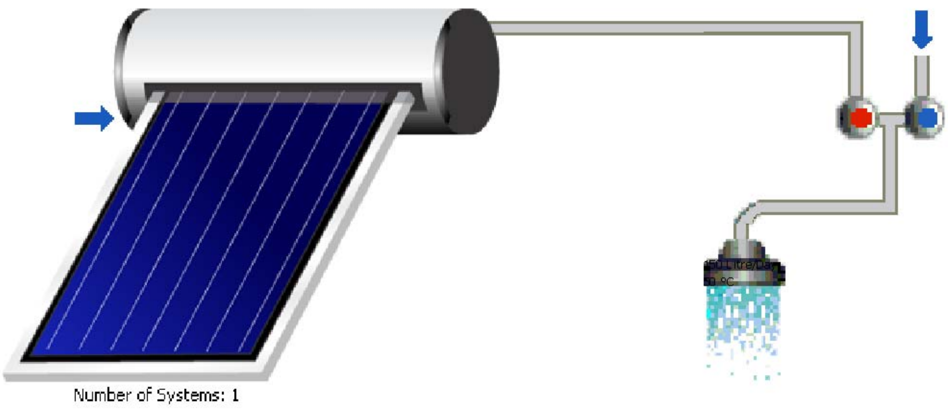
Legend

1	Collector Surface Area Irradiation (Active Surface)	6.405 kWh
1.1	Optical Collector Losses	1.821 kWh
1.2	Thermal Collector Losses	1.397 kWh
2	Energy from Collector Array	3.188 kWh
2.1	Solar Energy to Storage Tank	2.861 kWh
2.5	Internal Piping Losses	281 kWh
2.6	External Piping Losses	46 kWh
3.1	Tank Losses	847 kWh
6.5	Heating Element	0 kWh
9	DHW Energy from Tank	2.011 kWh

Glossary

1 Collector Surface Area Irradiation (Active Surface)
Energy Irradiated onto Tilted Collector Area (Active Solar Surface)
1.1 Optical Collector Losses
Reflection and Other Losses
1.2 Thermal Collector Losses
Heat Conduction and Other Losses
2 Energy from Collector Array
Energy Output at Collector Array Outlet (i.e. Before the Piping)
2.1 Solar Energy to Storage Tank
Energy from Collector Loop to Storage Tank (Minus Piping Losses)
2.5 Internal Piping Losses
Internal Piping Losses
2.6 External Piping Losses
External Piping Losses
3.1 Tank Losses
Heat Losses via Surface Area
6.5 Heating Element
Energy from Heating Element
9 DHW Energy from Tank
Heat for DHW Appliances from Tank (Exluding Circulation)

4.4 T-Sol Calculation Johannesburg



Installed Collector Power:	2,10 kW	
Installed Gross Solar Surface Area:	3 m²	
Collector Surface Area Irradiation (Active Surface):	6,67 MWh	2.224,34 kWh/m²
Energy Produced by Collectors:	3,27 MWh	1.090,29 kWh/m²
Energy Produced by Collector Loop:	2.945,87 kWh	981,96 kWh/m²
DHW Heating Energy Supply:	2046,76 kWh	
Solar Contribution to DHW:	2945,87 kWh	
Electricity Savings:		**3.776,8 kWh**
CO2 Emissions Avoided:		**2.515,32 kg**
DHW Solar Fraction:		**100,0 %**
Fractional Energy Saving (EN 12976):		**97,3 %**
System Efficiency:		**44,1 %**

Basic Data

Climate File

Location:	Johannesburg
Climate Data Record:	"Johannesburg SF"
Total Annual Global Radiation:	2075,08 kWh
Latitude:	-26,2 °
Longitude:	-28,03 °

Domestic Hot Water

Average Daily Consumption:	150 l
Desired Temperature:	50 °C
Load Profile:	Detached House (evening max)
Cold Water Temperature:	February:18 °C / August:15 °C
Circulation:	No

System

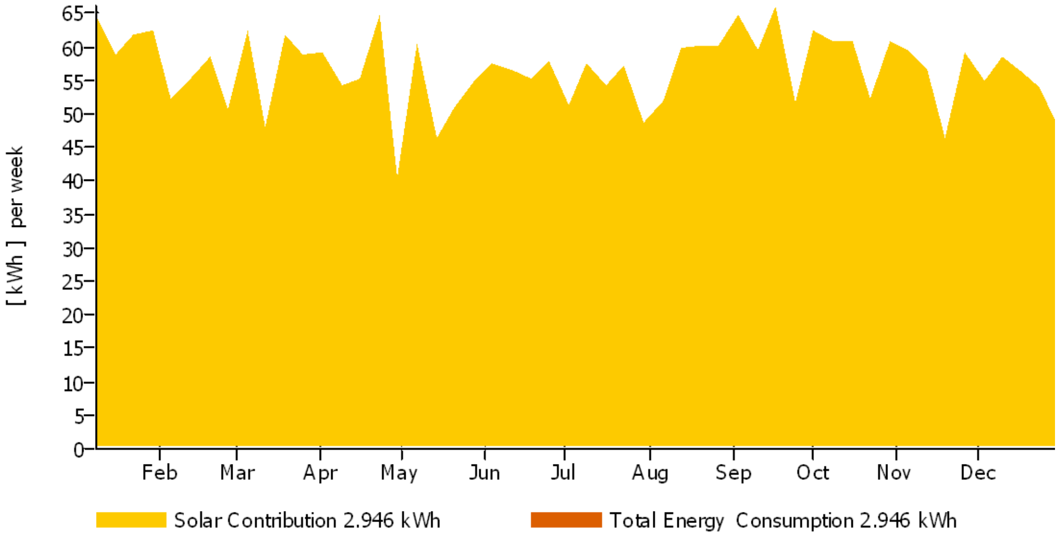
Thermosyphon System

Collector Area (Active Solar Surface):	3 m²
Type:	Standard Flat-Plate Collector
Tilt Angle:	30 °
Azimuth:	0 °
Storage Tank Volume:	200 l

Legend

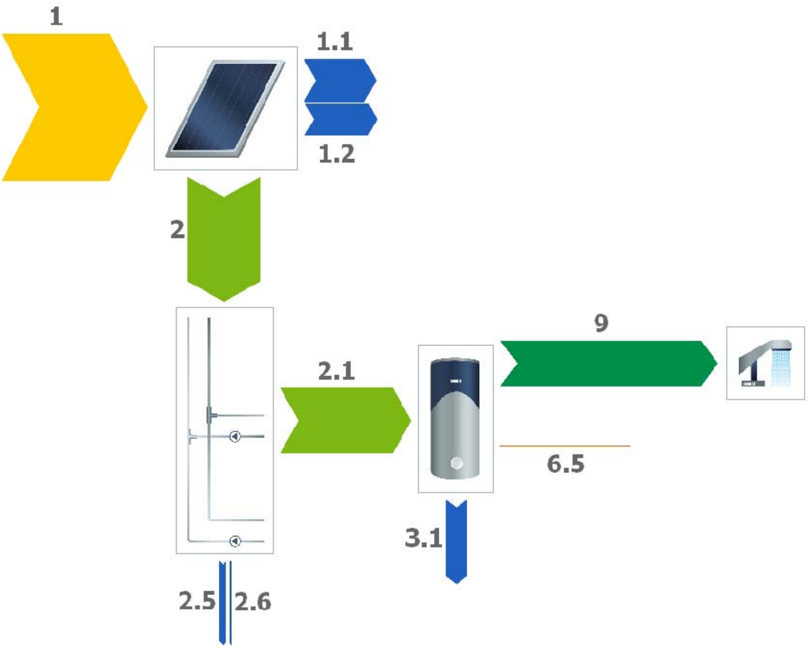
Original T*SOL Database
With Test Report
Solar Keymark

Solar Energy Consumption as Percentage of Total Consumption



These calculations were carried out by T*SOL Expert 4.5 - the Simulation Programme for Solar Thermal Heating Systems. The results are determined by a mathematical model calculation with variable time steps of up to 6 minutes. Actual yields can deviate from these values due to

Energy Balance Schematic



Legend

1	Collector Surface Area Irradiation (Active Surface)	6.673 kWh
1.1	Optical Collector Losses	1.964 kWh
1.2	Thermal Collector Losses	1.438 kWh
2	Energy from Collector Array	3.271 kWh
2.1	Solar Energy to Storage Tank	2.946 kWh
2.5	Internal Piping Losses	277 kWh
2.6	External Piping Losses	48 kWh
3.1	Tank Losses	897 kWh
6.5	Heating Element	0 kWh
9	DHW Energy from Tank	2.047 kWh

Glossary

1 Collector Surface Area Irradiation (Active Surface)
Energy Irradiated onto Tilted Collector Area (Active Solar Surface)
1.1 Optical Collector Losses
Reflection and Other Losses
1.2 Thermal Collector Losses
Heat Conduction and Other Losses
2 Energy from Collector Array
Energy Output at Collector Array Outlet (i.e. Before the Piping)
2.1 Solar Energy to Storage Tank
Energy from Collector Loop to Storage Tank (Minus Piping Losses)
2.5 Internal Piping Losses
Internal Piping Losses
2.6 External Piping Losses
External Piping Losses
3.1 Tank Losses
Heat Losses via Surface Area
6.5 Heating Element
Energy from Heating Element
9 DHW Energy from Tank
Heat for DHW Appliances from Tank (Exluding Circulation)