Design Principles of Solar Thermal Systems  
Results from Simulation and Experiences  

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**Keywords**: Requirements for economic efficient solar thermal systems. Computer tools on the market. Input data for simulations. Influence factors to the heat output of solar thermal systems. Solar hot water systems in different climates: Design principles for energy economic solutions. Solar Combisystems: Requirements and design.

1. **Background**

The economic efficiency of solar heating systems depends mainly on its design. Thus, the optimal design of all components of the system - collector, storage, tanks, pumps, control mechanism and piping - is essential as well as the design of collector area and storage volume as a function of the daily / hourly hot water demand. The useful heat output of a collector system depends also on the influencing meteorological quantities at the location, as well as on the structure of consumption.

For the system efficiency, the heat management philosophy is important: priority is given to the load (DHW or space heating) with the lowest temperature level, so that the solar collector works with the highest efficiency. Thus, the implementation of thermal storage in a solar system and its volume, depending on storage capacity and the application, is of great importance for the efficiency and the solar share of a heating system. The storage concept comprises the strategies - which are adjusted to the particular design of the collector area - for loading and discharging as well as for additional heating. Typical and practically proved storage concepts for solar thermal systems are one-storage- and multi-storage-systems adjusted to loading and discharging strategies with collector characteristics and the heat demand; Figure 1. Through thermal layers and loading of several stores according to priorities, respectively, a favorable as possible adjustment between solar heat gain and the effect of the solar installation is aimed at; Figure 2a and 2b.. This type of storage represents an ideal thermal storage. The inlet/outlet levels can be changed and may be considered as an advanced solar system for domestic hot water and space heating concept. Thermally stratified water tanks improve the annual system efficiency by about 20% and more.

To reduce the heat losses of the heat distribution system in larger buildings with more consumers a combination of buffer storage and decentralized stores as well as decentralized heat exchangers may be a more efficient and cost-effective solution; Figure 3a and 3b.

2. **Simulation tools**

There are several computer programs on the market for the thermal performance calculation of solar heating systems: Austrosol/Eurosol, Polysun, TSOL and SHWwin. All are transient simulation programs with time steps of a few minutes and feature database support for components and systems. Heat loads can also be defined in great detail. Possible system layouts are, however, restricted and differ from one program to the other.
The general program structure is shown in Figure 4. Most of the computer programs are based on hour-by-hour simulations to yield monthly and yearly performance estimates. With the same input data, the results of the most on the market offered PC tools are comparable; Figure 5. A more general computer program is TRNSYS, i.e. solar heating systems can be composed from TRNSYS modules. Within IEA-SHC-Task 26, about half of the solar combisystems from the 2000 overview is being modeled using TRNSYS, so that optimization of these system concepts can be calculated. A new version (2003) of SHWwin (2003, /2/) is using the input data and experimental data of Austrosol/Eurosol /1/. SHWwin is used for the following simulations.

For the simulation of solar thermal systems, meteorological data from all parts of the world is needed. For many regions, measured data may only be applied within a radius of 50 km from weather stations. This makes it necessary to interpolate parameters between stations.

METEONORM /3/ is a global meteorological database for solar energy and applied climatology. The method enables the data to be interpolated and monthly values to be obtained for almost all points of the globe. With the database in METEONORM it is possible to simulate solar energy systems in all parts of the world on a consistent basis. The interpolation errors are within the variations of climate from one year to the next.

The assurance of results from simulations is depending from the input-data, also considering the site conditions, the system design and the application, e.g. required heat demand.

The tools offer defaults with input-data based on experimental data, /e.g. /1/ and /2/. The users can edit the data.

Main influence factors to the output – heat production on daily, monthly and annual basis - are:

- Meteorological conditions on site:
  - Availability of absorbed solar radiation on collector area (shading, dust and snow on collector surface).
  - Ground reflection of solar radiation (albedo).

- Heat demand:
  - Day profiles on hourly basis.
  - Week profiles on daily basis.
  - Month profile on weekly basis.

- Water temperature:
  - Collector-inlet and outlet-temperature.

- Collector type, collector-loop and collector-connection:
  - Collector-Type:
    - Characteristically collector data, depending from type and product: Conversion factor and heat loss coefficient (certificated data).
  - Connection of collectors: hydraulic schemata.
  - Collector area.
  - Collector loop:
pipes length and diameter, insulation, heat exchanger;
high-flow systems, low-flow systems, drain-back systems (protection of both overheating and freezing of fluid in the solar collector loop).

- Storage:
  - Amount of stores, volume, combination of two and more stores, height and length, insulation, loading and discharging strategy, ambient temperature.
  - System integration, including regulation.

Proved simulation tools will allow the pre-design of solar thermal systems in an easy and short way. For simple hot water systems – compact systems – no extra simulation work will be necessary. For more complicated systems – hot water systems for apartment housing, settlements, commercial buildings as well as solar combisystems – additional detailed simulation is recommended, in combination with a sensibility analysis: “energy economic-design”.

3. Design of solar hot water systems

In new buildings solar systems for hot water preparation is today standard in many countries. In the area of building renovation, solar hot water preparation is attractive to increase the efficiency of heating systems. Especially ineffective heating systems for hot water preparation outside the heating season have been replaced by solar hot water preparation. Thus pollutant emissions through heating (wood, coal, oil boilers) could be reduced and at the same time a high comfort in hot water preparation could be reached. Figure 6a and 6b illustrate solar thermal systems in housing, with roof and façade integrated collectors.

In solar systems for hot water preparation flat plate collectors of different designs (non evacuated and evacuated collectors with and without selective coating) are used. Concentrating solar systems are only of interest in regions with high sunshine duration (direct beam). The selection of the collector type depends on the application and the temperature which has to be reached. For domestic hot water preparation the use of flat plate collectors with selective coating may be in many cases the most cost effective solution. For higher temperatures (above 80°C) and lower solar irradiation evacuated collectors would be more successful.

The optimal design of all components of the system - collector, storage, tanks, pumps, control mechanism and piping - is essential as well as the design of collector area and storage volume as a function of the daily energy demand.

The design of a solar heating system has to consider the meteorological conditions on site. The intensity of the solar radiation on a flat surface is higher when it is titled towards the sun. The maximum intensity occurs when the flat surface is perpendicular to the sun’s rays. Two-axis tracking of absorbers may thus maximize the energy gain at the expense of technical complexity. For fixed absorber surfaces, the energy gain is a function of the slope angle (0° = horizontal, 90° = vertical) and the azimuth angle (0° = South, -90° = East, +90° = West and 180° = North). The distribution of the annual incident energy on a tilted surface as a function of slope and azimuth has to be considered within the installation as well as integration of solar thermal collectors in building envelope.
The annual and monthly solar radiation in different climates of Europe is shown in Figure 7 to Figure 10. Die optimal collector inclination is shown in Figure 10. Nevertheless, the distribution of the annual incident energy on a tilted surface gives some freedom on choosing acceptable surfaces for collection of solar energy.

The integration of the collectors in the building should consider architectural rules and for the location specific building traditions. Solar collectors should be integrated in the building envelope (roof, façade), considering architectural rules and for the location specific building traditions. Orientation is best between 30° east and 45° west. Façade collectors will be used in urban buildings, where sufficient suitable and oriented roof for the installation of solar collectors is not available. A collector element directly integrated in the façade is understood by both solar collector and heat insulation of the building envelope. Advantages of faced integrated collectors are: Cost saving as a result of joint use of building components, replacement of the conventional façade, and suitable both for new buildings and for the renovation of old buildings. Compared with tilted collector areas, the absorbed solar radiation is reduced by about 25% to 30% as an average; Figure 8. The difference during the heating season is smaller; Figure 9. From the energetic point of view, façade integrated collectors are acceptable in solar combined heating systems with an oversized collector area for hot water preparation outside the heating season.

The use of solar hot water systems in an apartment house has the advantage of lower specific investment costs and thus the heat production costs can be reduced in comparison with small, decentralized systems; Figure 11 to Figure 13. The possibilities for a central hot water preparation in multifamily-buildings are used increasingly on the market nowadays.

The design of a solar hot water system should be oriented on the hot water demand outside the heating season. Under the typical meteorological conditions in temperate climates the annual solar share for hot water preparation - considering also economical aspects and in dependence on the daily hot water demand - should be in the range of about 60% to 70%, during the summer period the solar share would be about 60% to 90%; Figure 14 to Figure 19. In multi-family houses – apartment houses - the solar share for hot water preparation will generally be below 50%, also for reasons of lack of space on the roof for the installation of collectors; Figure 20 to Figure 22.

Solar hot water preparation is nearly similar in all climates during the summer period; Figure 14 to Figure 22.

Guidelines for energy-economic solutions are based not only simulation work but on long-term experiences. The storage volume is of about 1.5 to 2.0 times of the daily hot water demand. An annual efficiency of the solar system of at least 30% is aimed at. On an annual average the solar share is of about 70% in single-family buildings and of about 40% in multifamily dwellings; Figure 23 and Figure 24.

4. Design of solar combisystems

At suitable locations solar supported space heating systems can be considered for low energy buildings; mainly detached and row housing. The reference housing are shown in Figure 25.
Efficient operating solar combined heating systems require high building insulation as well as low-temperature heat distribution; Figure 26. Figure 27 illustrates the space heat demand for detached houses, depending from building envelope standard and climates.

The design of collector area and storage volume as well as the storage strategy are of great importance. If the solar system is combined with a space heating system and some solar heat is used for heating purposes, the collector area as well as the storage volume have to be increased. In this case there exists some unused solar heat in the period without space heat demand. An efficient use of solar heat can be reached if an additional heat demand exists during the summer period. Typical examples are the operation of an outdoor swimming pool or the heating up of soil by operating a solar supported ground-coupled heat pump system. In cold climates solar heat will provide the living quality also during the summer month.

If the contribution of solar energy for the heating of residential buildings is over 40% then the collector area and the storage volume have to be increased. Here a storage for several days is not sufficient any longer, solar energy for the heating period has to be provided by seasonal heat storage during the summer months. For a solar coverage of more than 80% for space heating and hot water preparation for a one-family house collector areas of 80 to 100 m² and a storage volume of 80 to 130 m³ are necessary. It will be difficult to realize these demands in detached houses, and then only in low-energy buildings and at high costs.

For solar-supported heating systems a combination with a biomass-burner or a heat pump are interesting solutions; Figure 28. An attractive auxiliary energy source for a solar thermal system is bioenergy. With a combined solar-biomass heating system the contribution to the heat need of a building (space heat and hot water) is covered to 100% by renewable energy sources. The ground coupled heat pump is primarily used for space heating during the heating period and the solar installation primarily for hot water preparation during the summer months. Long-term measurements of well designed ground coupled heat pump systems show, that the temperature within the soil reaches the same level after the summer period. This confirms the assumption that a complete heat recovery of the soil via solar radiation is possible. The heat extracted from the soil is therefore “stored solar energy” and a renewable ("sustainable") source of energy.

Considering energy-economic aspects, the annual solar share for heat production (hot water and space heating) ranges from 20%/year to 60%/year, depending from climate and building envelope standard; Figure 29 to Figure 31.

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/1/ AUSTROSOL/EUROSOL: EDV-Design Tool for Solar Thermal Systems
SOLPROS, Finland and Gerhard Faninger, University of Klagenfurt

/2/ SHWwin: EDV tool for the design of solar thermal systems for hot water preparation, solar combisystems, and solar supported district heating.
Institut für Wärmetechnik, Technical University of Graz, Austria
Free download from internet: http://wt.tu-graz.ac.at

/3/ METEONORM: published by Meteotest, Fabrikstrasse 14, CH-3012 Bern, and supported by the Swiss Federal Office of Energy.
Design Principles for Sustainable Solar Housing

Results from Simulation and Experiences
Fig. 1: Storage concepts for solar thermal systems
Fig. 2a: Solar thermal system with loading through thermal layers

Fig. 2b: Solar thermal system with loading through thermal layers
Fig. 3a: Solar thermal system with central storage in combination with decentralised hot water stores

Fig. 3b: Solar thermal system with central storage in combination with decentralised heat exchangers
Fig. 4: Program structure of PC-tools: Example Eurosol

Fig. 5: Comparison of PC-tools
Fig. 6a: Solar heating systems with roof collectors

Fig. 6b: Solar-combined heating systems with facade collectors
Fig. 7: Global solar radiation on horizontal surface
Fig. 9: Absorbed solar radiation during heating season: Influence of inclination and azimuth

Fig. 10: Absorbed solar radiation on tilted surface
Fig. 11: Collector costs and collector area

Fig. 12: Collector area and solar system costs
SOLAR THERMAL SYSTEMS FOR HOT WATER

HEAT PRODUCTION COSTS

Costs, EUR/kWh

0,30
0,25
0,20
0,15
0,10
0,05
0,00

0 10 20 30 40 50 60 70 80 90 100
Collector area, m²

Life Time of Solar System
- 15 years
- 20 years
- 25 years
- 30 years

Annual Solar Share: 45% - 50%
Location: Vienna / Austria
Heat production costs of solar thermal systems

Fig. 13: Heat production costs of solar thermal systems

SOLAR HOT WATER SYSTEM FOR DETACHED AND ROW HOUSING

Fig. 14: Solar heating systems with roof collectors:
Reference housing: Detached and row housing
Fig. 15: Location and solar share

Fig. 16: Design of collector area and storage volume:

Non-selective collector
Fig. 17: Design of collector area and storage volume:
Selective collector

Fig. 18: Design of collector area and storage volume:
Evacuated collector
**SOLAR HEATING SYSTEM FOR HOT WATER**

Compact system for household

*Inclination and heat output*

**Solar share, %/a**

<table>
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<tr>
<th>Location</th>
<th>Inclination 45°</th>
<th>Inclination 90° (vertical)</th>
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<tr>
<td>Stockholm</td>
<td>65% 61%</td>
<td>65% 61%</td>
</tr>
<tr>
<td>Zurich</td>
<td>75% 57%</td>
<td>75% 57%</td>
</tr>
<tr>
<td>Milan</td>
<td>80% 67%</td>
<td>80% 67%</td>
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Selective flat plate collector: 8 m² & 500 litre storage
Hot water demand: 120 litre/day (50°C)
Azimuth: 0° (south)

Fig. 19: Inclination and heat output

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**SOLAR HOT WATER SYSTEM FOR APARTMENT HOUSING**

Fig. 20: Solar hot water system for apartment housing
Fig. 21: Collector-type and solar share

Fig. 22: Collector inclination and heat output
Fig. 23: Energy-economic design of solar hot water system

Fig. 24: Solar share and heat production costs
SOLAR COMBISYSTEMS FOR DETACHED AND ROW HOUSING

Fig. 25: Solar combisystems:
Reference housing: Detached and row housing

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<td>≤0.20</td>
<td>≤0.15</td>
<td>≤0.10</td>
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<tr>
<td>Outside Window</td>
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<td>≤1.10</td>
<td>≤0.70</td>
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<td>Ceiling/Basement</td>
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<td>≤0.30</td>
<td>≤0.20</td>
<td>≤0.13</td>
<td>≤0.13</td>
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Fig. 26: Typically U-values for different building standards in Austria
Fig. 27: Building envelope and space heat demand

Fig. 28: Solar Combisystems
Fig. 29a: Solar Combisystems: Selective collector
25 m² collector & 2 m³ water tank

Fig. 29b: Solar Combisystems: Selective collector
50 m² collector & 5 m³ water tank
Fig. 30a: Solar Combisystems: *Evacuated collector*
*25 m² collector & 2 m³ water tank*

Fig. 30b: Solar Combisystems: *Evacuated collector*
*50 m² collector & 5 m³ water tank*
Fig. 31a: Solar Combsystems: Collector area and storage volume

Fig. 31b: Solar Combsystems: Collector area and storage volume
Fig. 31c: Solar Combsystems:
Collector area and storage volume

Fig. 31d: Solar Combsystems:
Collector area and storage volume
Fig. 31e: Solar Combisystems: Collector area and storage volume

Fig. 31f: Solar Combisystems: Collector area and storage volume