Solar Space Cooling and Heating and Hot Water Production for a House

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Abstract: - Heating and cooling of buildings require a large amount of energy. For countries with good solar potential, solar energy can be considered a viable option for these applications. With the increased price of fuels solar space heating became a viable option however the potential problem of such a system is that a lot of solar energy collectors need to be disconnected or shaded during summertime. Solar cooling offers possibilities of using the same solar collectors for space cooling as well through an absorption chiller. To be viable solar space heating systems need to utilize a low temperature supply system such as air system. Absorption units on the other hand require temperature of the order of 90°C but the system during summertime is more effective and the available solar radiation is much more than the wintertime. A system suitable for a typical 196 m^2 house is modelled and simulated with TRNSYS program. The house is located in Nicosia, Cyprus, 35° North latitude having mild winters and severe summers. Three different types of solar collectors are considered a flat plate, advance flat plate and evacuated tube collectors. The results show that the optimum system consists of 1.5 m^3 storage tank and 30 m^2 evacuated tube collectors installed at an inclination equal to 30° and operated at a water flow rate of 36 kg/hr-m^2. The annual solar contribution is about 55% and the economic analysis performed showed the system is viable as positive life cycle savings are obtained (5100 Euro). Therefore it can be concluded that solar energy should be used whenever possible.

1 Introduction

Man realised that a good use of solar energy is in his benefit, from the prehistoric times. The first findings were related to the domestic life. The Greek historian Xenophon in his "memorabilia" records some of the teachings of the Greek Philosopher Socrates (470 - 399 BC) regarding the correct orientation of dwellings in order to have houses which were cool in summer and warm in winter. Since man began to reason, he has recognised the sun as a motive power behind every natural phenomenon. This is why many of the pre-historic tribes considered Sun as "God". Many scripts of ancient Egypt say that the Great Pyramid, one of the man's greatest engineering achievements, was built as a stairway to the sun (Anderson, 1977).

There are many alternative energy sources which can be used instead of fossil fuels. The decision as to what type of energy source should be utilised must, in each case, be made on the basis of economic, environmental and safety considerations. Because of the desirable environmental and safety aspects it is widely believed that solar energy should be utilised instead of other alternative energy forms.

In addition to the thousands of ways in which the sun's energy has been used by both nature and man through time, to grow food or dry clothes, it has also been deliberately harnessed to heat and cool buildings (both active and passive), to heat water for domestic and industrial uses, to heat swimming pools, to power refrigerators, to operate engines and pumps, to desalinate water for drinking purposes, to generate electricity, to produce various chemicals such as hydrogen, and many more.

The objective of this paper is to present the design of a complete solar system for space heating, cooling and hot water production. The various types of collectors that can be used for this purpose are examined with respect to the economic viability of such system located in Nicosia, Cyprus having hot summers and mild winters. The optimum slope, flow rate and area of the solar system is determined as well as the optimum storage tank size.

2 Solar Collectors

Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector, which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (air, water, or heat transfer oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which can be drawn for use at night and/or cloudy days.

Solar energy collectors are basically distinguished by their motion as stationary or tracking and their operating temperature. Due to the increased maintenance requirements for domestic applications only stationary solar collectors are used. These collectors are permanently fixed in position and do not track the sun. Three types of collectors fall in this category:

1. Flat plate collector (FPC)
2. Stationary compound parabolic collector (CPC)
3. Evacuated tube collector (ETC)

In the present application only the flat-plate and evacuated tube collectors are considered which are industrially available.

The most used type of collectors is the flat-plate. When solar radiation passes through a transparent cover and impinges on the blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and then transferred to the transport medium in the fluid tubes to be carried away for storage or use. The underside of the absorber plate and the side of casing are well insulated to reduce conduction losses. The liquid tubes can be welded to the absorbing plate, or they can be an integral part of the plate. The liquid tubes are connected at both ends by large diameter header tubes. The transparent cover is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. It also reduces radiation losses from the collector as the glass is transparent to the short wave radiation received by the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate (greenhouse effect).

Flat plate collectors are usually permanently fixed in position and require no tracking of the sun. The collectors should be oriented directly towards the equator, facing south in the northern hemisphere and north in the southern. The characteristics of a typical water flat plate collector considered in this work are shown in Table 1.

The performance of flat-plate collectors depend greatly on the way fins are attached to the riser tubes. Best results are obtained by welding the fins on the pipes. Lately some modern manufacturing techniques have been introduced by the industry like the use of ultrasonic welding machines, which improve both the speed and the quality of welds. The greatest advantage of this method is that the welding is performed at room temperature therefore deformation of the welded parts is avoided. These collectors with selective coating are called advance flat plate collectors and the characteristics of a typical type are also shown in Table 1.

Conventional flat-plate solar collectors were developed for use in sunny and warm climates. Their benefits however are greatly reduced when conditions become unfavourable during cold, cloudy and windy days. Evacuated heat pipe solar collectors (tubes) operate differently than the flat-plate collectors. These consist of a heat pipe inside a vacuum-sealed tube. The vacuum envelope reduces convection and conduction losses, so the collectors can operate at higher temperatures than flat-plate collectors. Like flat-plate collectors, they collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles.

Evacuated tube collectors use liquid-vapour phase change materials to transfer heat at high efficiency. These collectors feature a heat pipe placed inside a vacuum-sealed tube. The pipe, which is a sealed copper pipe, is then attached to a black copper fin that fills the tube (absorber plate). Protruding from the top of each tube is a metal tip attached to the sealed pipe (condenser). The heat pipe contains a small amount of fluid (e.g. methanol) that undergoes an evaporating-condensing cycle. In this cycle, solar heat evaporates the liquid, and the vapour travels to the heat sink region where it condenses and releases its latent heat. The condensed fluid return back to the solar collector and the process is repeated. When these tubes are mounted, the metal tips up, into a manifold to transfer the heat away to storage or use. Water, or glycol, flows through the manifold which circulates through a heat exchanger and gives off its heat to the water stored in a solar storage tank.

Table1 Characteristics of a typical flat plate collector (FPC) and advance flat plate collector (AFP) systems

Parameter	Simple FPC	AFP collector
Fixing of risers on the absorber plate	Embedded	Ultrasonically welded
Absorber coating	Black mat paint	Chromium selective coating
Glazing	Low-iron glass	Low-iron glass
Efficiency mode	$n\ v_s\ (T_i - T_a)/G$	$n\ v_s\ (T_i - T_a)/G$
G_{test} – flow rate at test conditions (kg/s-m^2)	0.015	0.015
a_o – intercept efficiency	0.79	0.80
a_1 – negative first-order coefficient (W/m^2 °C)	6.67	4.78
b_o – incidence angle modifier constant	0.1	0.1

Because no evaporation or condensation above the phase-change temperature is possible, the heat pipe offers inherent protection from freezing and overheating. This self-limiting temperature control is a unique feature of the evacuated tube collector. The characteristics of a typical evacuated tube collector considered in this work are shown in Table 2.

Table 2 Characteristics of a typical evacuated tube collector (ETC) system

Parameter	Value
Glass tube diameter	65mm
Glass thickness	1.6mm
Collector length	1965mm
Absorber plate	Copper
Coating	Selective
Absorber area for each collector	$0.1m^2$
Efficiency mode	$n\ v_s\ (T_i - T_a)/G$
G_{test} – flow rate at test (kg/s m^2)	0.014
a_o – intercept efficiency	0.82
a_1 – -ve first-order coef.(W/m^2 °C)	2.19
b_o – incidence angle modifier const	0.2

3 Solar Water Heating Systems

The main part of a solar water heating system is the solar collector array that absorbs solar radiation and converts it to heat. This heat is then absorbed by a heat transfer fluid (water, non-freezing liquid, or air) that passes through the collector. This heat can then be stored or used directly. Portions of the solar energy system are exposed to the weather conditions, so they must be protected from freezing and from overheating caused by high insolation levels during periods of low energy demand.

In solar water heating systems, potable water can either be heated directly in the collector (direct systems) or indirectly by a heat transfer fluid that is heated in the collector and passes through a heat exchanger to transfer its heat to the domestic or service water (indirect systems). The heat transfer fluid is transported either naturally (passive systems) or by forced circulation (active systems). Natural circulation occurs by natural convection (thermosyphoning), whereas for the forced circulation systems pumps or fans are used. Except for thermosyphon and integrated collector storage systems, which need no control, solar domestic and service hot water systems are controlled using differential thermostats.

Five types of solar energy systems can be used to heat domestic and service hot water: thermosyphon, integrated collector storage, direct circulation, indirect, and air. The first two are called passive systems as no pump is employed whereas the others are called active systems because a pump or fan is employed in order to circulate the fluid. For the complete space heating, cooling and hot water system considered in this work active systems are usually employed. Passive systems are mostly suitable for domestic hot water production only and thus they will not be considered in this work. For freeze protection, recirculation and drain-down are used for direct solar water heating systems and drain-back is used for indirect water heating systems. More details on these systems can be found in Kalogirou (2004). A wide range of collectors have been used for solar water heating systems. A review of the systems is given in (Morrison & Wood, 1999; Kalogirou, 2004).

4 Solar Space Heating and Cooling

The systems discussed in section 3 may be combined to create a wide variety of building solar heating and cooling systems. Solar radiation is collected by solar collectors, thermal energy is stored in a storage tank, and transportation of fluid media is done mostly by mechanical means.

Systems for space heating are very similar to those for water heating and the same considerations for combination with an auxiliary source, boiling and freezing, controls, etc., apply to both. The most common heat transfer fluids are water, water and antifreeze mixtures and air. The load is the building to be heated or cooled. Although it is technically possible to construct a solar heating or cooling system which can satisfy 100% the design load, such a system would be non-viable since it would be oversized for most of the time. The size of the solar system may be determined by a life-cycle cost analysis (see section 5.4).

Active solar space systems use collectors to heat a fluid, storage units to store solar energy until needed, and distribution equipment to provide the solar energy to the heated spaces in a controlled manner. A complete system includes additionally pumps or fans for transferring the energy to storage or to the load which require a continuous availability of non-renewable energy, generally in the form of electricity.

The load can be space cooling, heating, or a combination of these two with hot water supply as in the present application. In combination with conventional heating equipment solar heating and cooling provides the same levels of comfort, temperature stability, and reliability as conventional systems.

During daytime the solar system absorbs solar radiation with collectors and conveys it to storage using a suitable fluid. As the building requires heat this is obtained from storage. Control of the solar system is exercised by differential temperature controllers, i.e., the controller compares the temperature of the collectors and storage and whenever the temperature difference is more than a certain value (7-10°C) the solar pump is switched ON. In locations where freezing conditions are possible to occur, a low-temperature sensor is installed on the collector which controls the solar pump when a pre-set temperature is reached. This process wastes some stored heat, but it prevents costly damages to the solar collectors.

Solar cooling of buildings is an attractive idea as the cooling loads and availability of solar radiation are in phase. Additionally, the combination of solar cooling and heating greatly improves the use factors of collectors compared to heating alone. Solar air conditioning can be accomplished by various types of systems but the most popular one is the absorption cycle. It should be noted that the same solar collectors are used for both space heating and cooling systems when both are present. A review of the various solar heating and cooling systems is presented by Hahne (1996).

4.1 Space Heating and Service Hot Water

It is useful to consider solar systems as having five basic modes of operation, depending on the conditions that exist in the system at a particular time (Duffie and Beckman, 1991):

1. If solar energy is available and heat is not needed in the building, energy gain from the collector is added to storage.
2. If solar energy is available and heat is needed in the building, energy gain from the collector is used to supply the building need.
3. If solar energy is not available, heat is needed in the building, and the storage unit has stored energy in it, the stored energy is used to supply the building need.
4. If solar energy is not available, heat is needed in the building, and the storage unit has been depleted, auxiliary energy is used to supply the building need.
5. The storage unit is fully heated, there are no loads to met, and the collector is absorbing heat.

When the last mode occurs, there is no way to use or store the collected energy, and this energy must be discarded. This can be achieved through the operation of pressure relief valves or if the stagnant temperature will not be detrimental to the collector materials, the flow of fluids is turned off, thus the collector temperature will rise until the absorbed energy is dissipated by thermal losses. This is more suitable to solar air collectors.

Additional operational modes can also be employed such as to provide service hot water. It is also possible to combine modes, i.e., to operate in more than one mode at a time. Moreover, many systems do not allow direct heating from solar collector to building but always transfer heat from collector to storage whenever this is available and from storage to load whenever needed. In Europe solar heating systems for combined space and water heating are known as combisystems. In the rest of this section the design of residential-scale water systems is described.

There are many variations of systems used for both solar space heating and service hot water production. The basic configuration is similar to the solar water heating systems outlined in section 3. When used for both space and hot water production this system allows independent control of the solar collector-storage and storage-auxiliary-load loops as solar-heated water can be added to storage at the same time that hot water is removed from storage to meet building loads. Usually, a bypass is provided around the storage tank to avoid heating the storage tank, which can be of considerable size, with auxiliary energy.

A detailed schematic of a liquid-based system is shown in Fig. 1. In this case a collector heat exchanger is shown between the collector and the storage tank, which allows the use of antifreeze solutions to the collector circuit. Relief valves are also required for dumping excess energy if the collector temperature reaches saturation. Means of extracting energy for service hot water are indicated. Auxiliary energy for heating is added so as to “top off” that available from solar energy system.

A load heat exchanger is shown in Fig. 1 to transfer energy from the tank to the air in the heated spaces. The load heat exchanger must be adequately designed to avoid excessive temperature drop and corresponding increase in the tank and collector temperatures.

Advantages of liquid heating systems include high collector F_R, smaller storage volume, and relatively easy adaptation to supply energy to absorption air conditioners (see next section).

4.2 Absorption units

Absorption is the process of attracting and holding moisture by substances called desiccants. Desiccants are sorbents, i.e., materials that have an ability to attract and hold other gases or liquids, which have a particular affinity for water. During absorption the desiccant undergoes a chemical change as it takes on moisture, e.g. the table salt, which changes from a solid to a liquid as it absorbs moisture. The characteristic of the binding of desiccants to moisture, makes the desiccants very useful in chemical separation processes (ASHRAE, 1989).

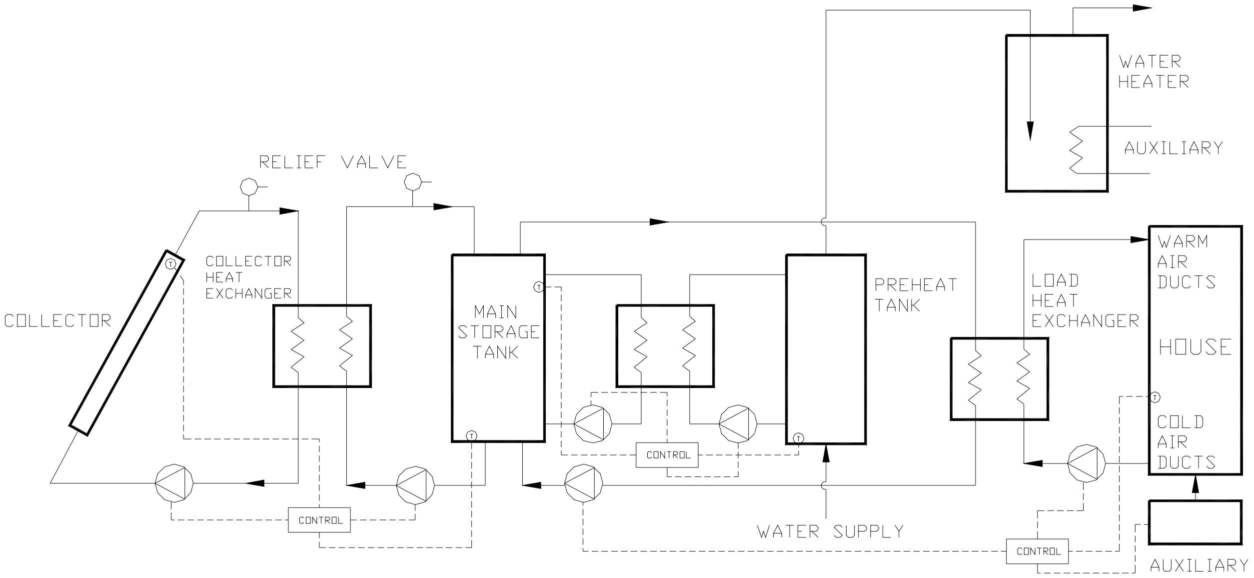


Fig. 1 Detail schematic of a solar water heating system

Absorption systems are similar to the vapour-compression ones but differ in the pressurisation stage. In general an absorbent, on the low-pressure side, absorbs an evaporating refrigerant. The most usual combinations of fluids include lithium bromide-water (LiBr-H_2O) where water vapour is the refrigerant and ammonia-water (NH_3-H_2O) systems where ammonia is the refrigerant.

The pressurisation is achieved by dissolving the refrigerant in the absorbent (Fig. 2). Subsequently, the solution is pumped to a high pressure with an ordinary liquid pump. The addition of heat in the generator is used to separate the low-boiling refrigerant from the solution. In this way the refrigerant vapour is compressed without the need of large amounts of mechanical energy that the vapour-compression air conditioning systems demand. The remainder of the system consists of a condenser, expansion valve and evaporator, which function in a similar way as in a vapour-compression air conditioning system.

The NH_3-H_2O system is more complicated than the LiBr-H_2O system, since it needs a rectifying column that assures that no water vapour enters the evaporator where it could freeze. The NH_3-H_2O system requires generator temperatures in the range of 125°C to 170°C with air-cooled absorber and condenser and 95°C to 120°C when water-cooling is used. These temperatures cannot be obtained with flat-plate collectors. The coefficient of performance (COP), which is defined as the ratio of the cooling effect to the heat input, is between 0.6 to 0.7 (Kalogirou *et al.*, 2001).

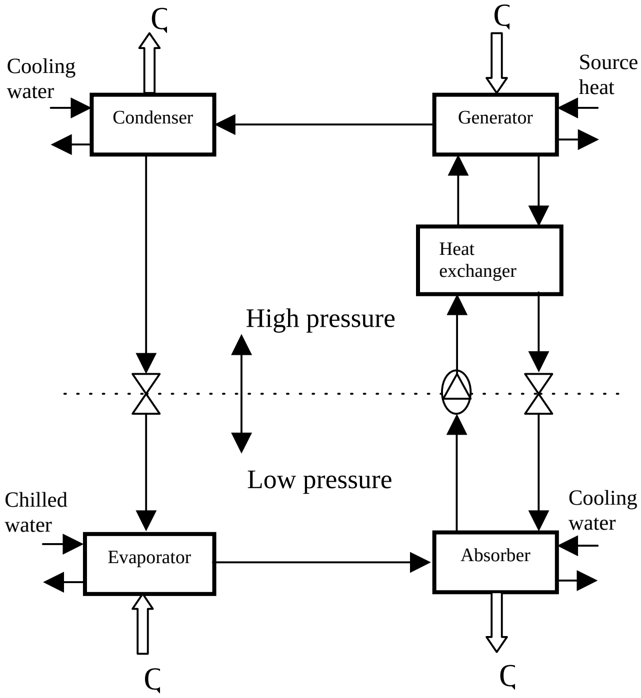


Fig. 2 Schematic of a single effect LiBr-water absorption system

The LiBr-H_2O system operates at a generator temperature in the range of 70°C to 95°C with water used as a coolant in the absorber and condenser and has COP higher than the NH_3-H_2O systems. The COP of this system is between 0.6 and 0.8 (Duffie and Beckman, 1991). A disadvantage of the LiBr-H_2O systems is that their evaporator cannot operate at temperatures much below 5°C since the refrigerant is water vapour. Commercially available absorption chillers for air conditioning applications usually operate with a solution of lithium bromide in water and use steam or hot water as the heat source. In the market two types of chillers are available, the single and the double effect.

The single effect absorption chiller is mainly used for building cooling loads, where chilled water is required at 6-7^{o}C. The COP will vary to a small extent with the heat source and cooling water temperatures. Single effect chillers can operate with hot water temperature ranging from about 80-150^{o}C when water is pressurised (Florides et al., 2002a). A method to design, construct and evaluate the performance of a single stage lithium bromide – water absorption machine is presented by Florides *et al.* (2003).

5 The Complete System

The objective of this work is to design a complete active solar space air conditioning (cooling and heating) system, together with a domestic water heating subsystem. Before giving the details of the complete system some design features of the individual solar systems are given.

5.1 Solar Heating and Hot Water System

A schematic diagram of a solar heating and hot water system is shown in Fig. 3. Control of the solar heating system is based on two thermostats; the collector-storage temperature differential, and the room temperature. The differential thermostat compares the temperature between the collector outlet and the bottom of the storage tank. When this difference exceeds a preset number of degrees (6 to 10°C), the collector pump is activated and continues to run until the temperature differential drops to near zero (1-2°C); the pump is turned off. When the room thermostat calls for heat, the load pump is activated, drawing heated water from the main storage tank to meet the demand. If the energy in the storage tank cannot meet the load demand, a second stage of the thermostat activates the auxiliary heater to supply the balance of the heating requirements. Usually, the controller modifies also the valves so that the flow is entirely through the auxiliary heater whenever the solar energy storage is unable to meet the load.

The collector-storage design shown in Fig. 3 is suitable for use in a non-freezing climate. To employ such a system in a freezing climate, provisions for complete and dependable drainage of the collector must be made. Collector drainage can be done through the installation of an automatic discharge valve, activated by the ambient temperature, and an air vent. This is called a drain-down system, where collector water is drained out of the system to waste. Alternatively, a drain-back system can be used in which the collector water is drained back to the storage whenever the solar pump stops. Air then enters the collector through a vent.

If the climate is characterized by frequent subfreezing temperatures, positive freeze protection through the use of an antifreeze solution in a closed collector loop is deemed necessary. The most usual solution is water plus glycol. In this case, a heat exchanger is employed in between the collector loop and the water storage tank, as shown schematically in Fig. 4. The intervention of a heat exchanger between the collector heat transfer fluid and the storage water introduces a temperature differential across the two sides, thereby lowering the storage tank temperature. This is a penalty for the system performance however this system design deserves favourable consideration to avoid the danger of malfunction in a self-draining system.

When a water-based solar system is used in conjunction with a warm air space heating system, the most economical means of auxiliary energy supply is by the use of a fossil-fuel-fired boiler. In case of bad weather, the boiler can take over the entire heating load.

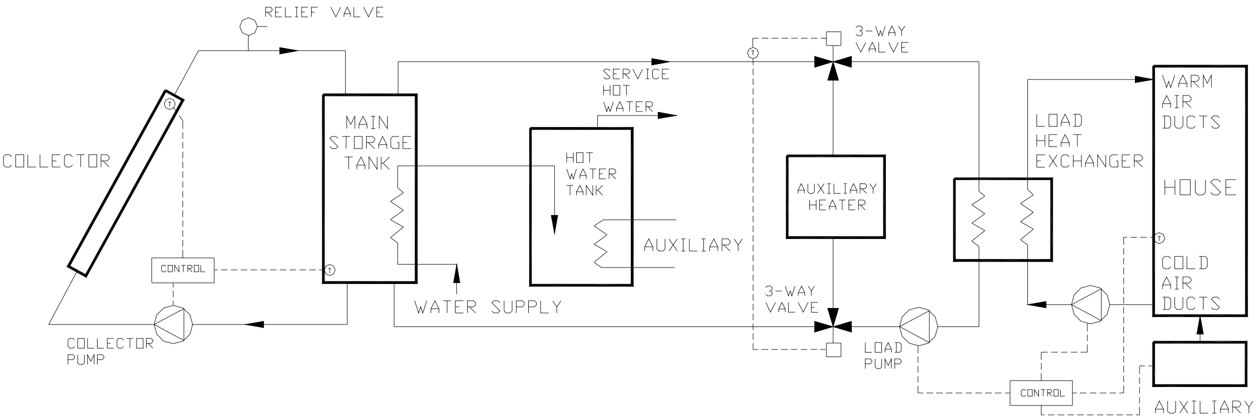


Fig. 3 Schematic diagram of a solar space heating and hot water system

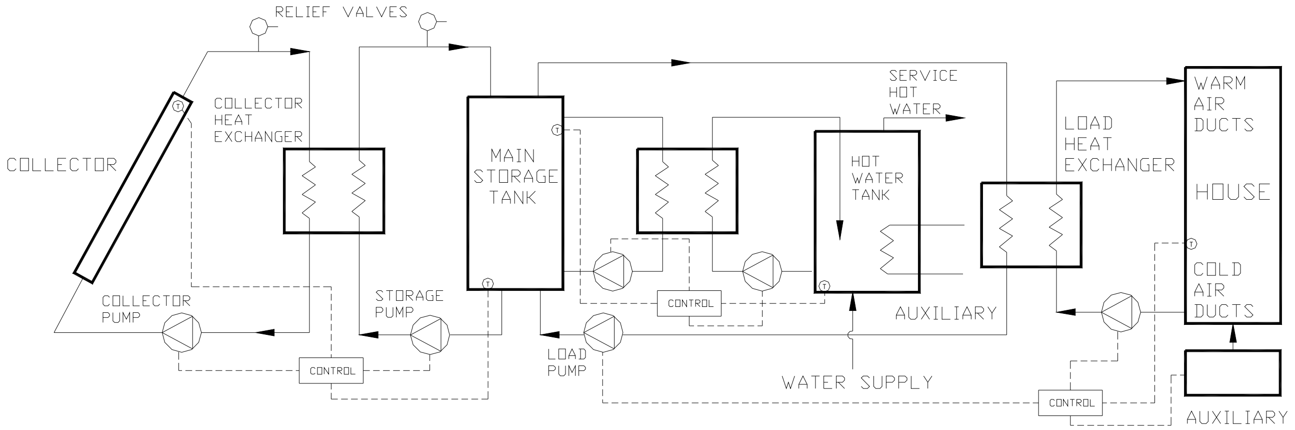
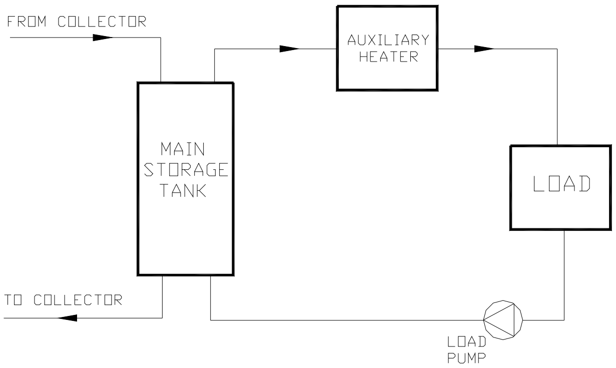


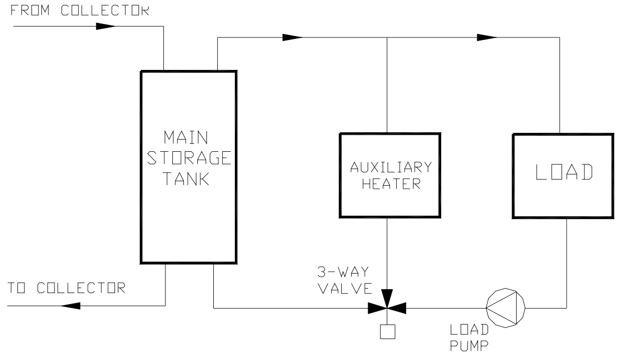
Fig. 4 Schematic diagram of space heating and hot water system with antifreeze solution

When a water-based solar system is used in conjunction with a water space heating system or to supply the heated water to an absorption air-conditioning unit, the auxiliary heater can be located in the storage-load loop, either in series or in parallel with the storage, as illustrated in Fig. 5. When auxiliary energy is employed to boost the temperature of solar-heated water as shown in Fig. 5a, maximum utilization of stored solar energy is achieved. This way of connecting the auxiliary supply, however, also has the tendency of boosting the storage tank temperature because water returning from the load may be at a higher temperature than the storage. Increasing the storage temperature by auxiliary energy has the undesirable effect of lowering the collector effectiveness, in addition to diverting the storage capacity to the storage of auxiliary energy instead of solar energy. This however depends on the operating temperature of the heating system. Therefore a low temperature system is required. This can be achieved with a water to air heat exchanger either centrally with an air handling unit or in a distributed way with individual fan coil units in each room to be heated. This system has the advantage of being able to be connected easily with space cooling system as for example with an absorption system as will be described in next section. By using this type of systems solar energy can be used more effectively as a high temperature system would imply that the hot water storage remains at high temperature thus solar collectors will work at lower efficiency.

Another possibility is to use under-floor heating or an all water system employing the traditional heating radiators. In this case provisions need to be made during the design stage to operate the system at low temperature which implies the use of bigger-size radiators. Such a system is also suitable for retrofit applications.



(a) in series with load



(b) parallel with load

Fig. 5 Auxiliary energy supply in water-based systems

Figure 5(b) illustrates an arrangement that makes it possible to isolate the auxiliary heating circuit from the storage. Solar-heated storage water is used exclusively to meet load demands when its temperature is adequate. When the storage temperature drops below the required level, circulation through the storage tank is discontinued and hot water from the auxiliary heater is used exclusively to meet space heating. This way of connecting the auxiliary supply avoids the undesirable increase of storage water temperature by auxiliary energy. However, it has the disadvantage that stored solar energy at lower temperatures is not fully utilized and this energy may be lost from the storage. The same requirements for a low temperature system apply here so as to be able to extract as much energy as possible from the storage.

To emphasize the importance of the bypass operation mentioned in the preceding paragraphs, a numerical example is given. Suppose that the required water temperature in the heating system is 90°C. When the storage temperature is only 70°C, the auxiliary could be used to raise the temperature to 90°C. However, the water temperature drop in the heating radiators is only 10°C or less. Thus the returning water from the radiators to the storage would be at 80°C. This is equivalent to the boosting of the storage with a 10°C temperature rise, thereby reducing the collector efficiency and useful solar energy storage. This example shows also the importance of using a low temperature heating system. However when the system is operating in cooling mode, where the operation temperature of the generation is of the order of 90°C, the solar system unavoidably works at higher temperature but this is not too much of a problem as during summertime a higher amount of solar radiation is available.

5.2 Solar Cooling System

The greatest disadvantage of solar heating system is that a large number of collectors need to be shaded or disconnected during summertime to reduce overheating. A way to avoid this problem and increase the viability of the solar system is to employ a combination of space heating and cooling.

This is economically viable when the same collector is used for both space heating and cooling. Flat-plate solar collectors are commonly used in solar space heating. However, because of the relatively low temperatures attainable by flat-plate collectors, only a few practical methods are available for flat-plate solar-operated cooling processes. One of the most promising schemes is the utilization of an absorption refrigeration cycle with solar energy serving as the source of heat to the generator.

Figure 6 shows schematically a solar-operated absorption refrigeration system. The refrigeration cycle is the same as the one discussed in Section 4.2. Due to the intermittent nature of available solar energy a hot water storage tank is needed, thus the collected energy is first stored in the tank and used as energy source in the generator to heat the strong solution when needed. For this purpose the same storage tank of the solar heating system is used. When the storage tank temperature is too low to be effective in the generator, augmentation of the water temperature takes place in the auxiliary heater. Again here the same auxiliary heater of the space heating system can be used. If the storage temperature is very low due to prolonged lack of sunshine, the storage is bypassed, as in space heating system, to avoid boosting of storage temperature by auxiliary energy, and the heating load of the generator is then entirely carried by the auxiliary heater.

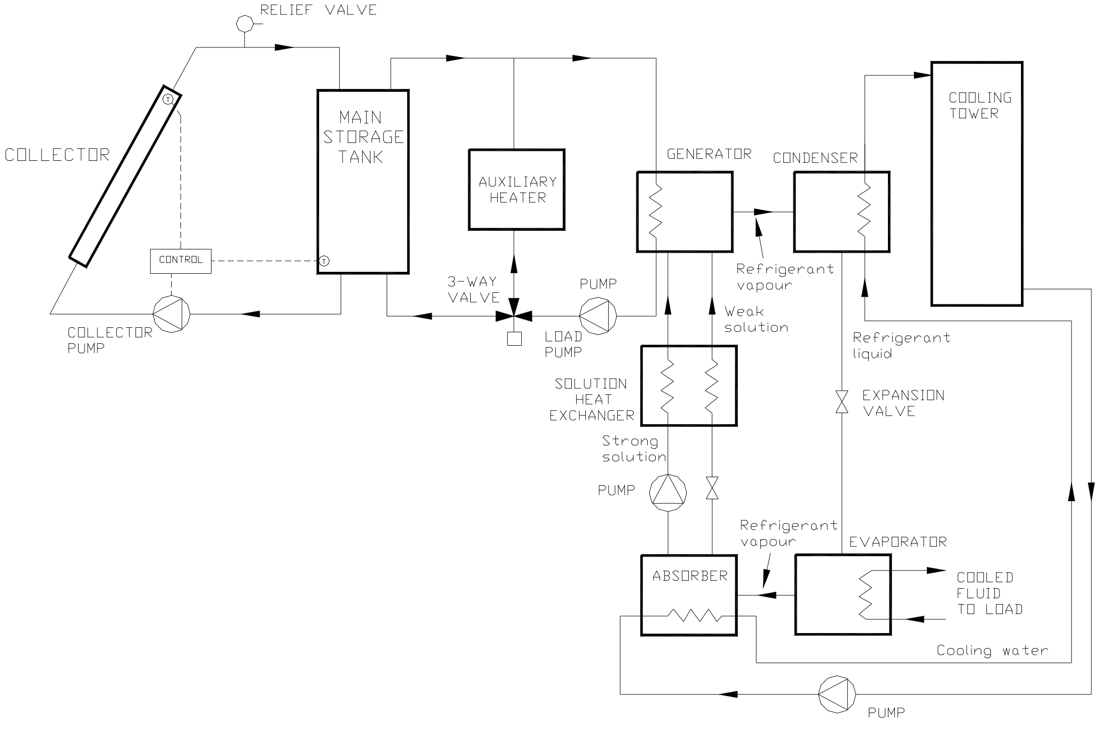


Fig. 6 Schematic diagram of a solar-operated absorption refrigeration system

It should be noted that the operating temperature range of the hot water supplied to the generator of a lithium bromide-water absorption refrigeration system is from 80 to 100°C. The lower temperature limit is imposed from the fact that hot water must be at a temperature sufficiently high (at least 80°C) to be effective for boiling the water from the solution in the generator. Also, the temperature of the concentrated lithium bromide solution on its return to the absorber must be kept high enough to prevent crystallisation of the lithium bromide. Usually an unpressurized water storage tank system is used and thus an upper limit of about 100°C is used to prevent water from boiling. In the present system a generator temperature of 93°C is considered which was found to be optimum for this type of systems (Florides et al., 2002b).

Since in an absorption-refrigeration cycle heat must be rejected from the absorber and the condenser an adequate cooling water system must be incorporated into the overall cycle. One way of providing cooling water is the use of a cooling tower as shown in Fig. 6. Cooled water emerging from the cooling tower is first fed to the absorber and then to the condenser, because the former generally requires a lower temperature than the latter. It should be noted that the use of a cooling tower in a small residential system is problematic both with respect to space and maintenance requirements, thus whenever possible water drawn from a well can be used.

Just as in the case of space heating, the auxiliary heater can be arranged in parallel with the storage tank instead of in-series and the solar collection can be made through a heat exchanger that keeps the collector liquid separate from the storage tank water.

5.3 Complete Solar System and System Model

A typical active solar space air conditioning (cooling and heating) system, together with a domestic water heating subsystem, is shown schematically in Fig. 7. Solar liquid-heating collectors are used to absorb and transform solar radiation into thermal energy of the transport medium. Water is used as both the heat transfer and the storage medium. The water heated by solar energy is pumped into the storage tank waiting to supply space and domestic water loads. A fossil-fuel-fired conventional heater is integrated with the solar system to provide an auxiliary energy supply should the solar system fail to meet the building energy requirement in case of cloudy weather.

The complete system located in Nicosia, Cyprus (latitude 35°) is simulated with TRNSYS program. The program consists of many subroutines that model subsystem components. With a program such as TRNSYS which has the capability of interconnecting system components in any desired manner, solving differential equations and facilitating information output, the entire problem of system simulation reduces to a problem of identifying all the components that comprise the particular system and formulating a general mathematical description of each.

TRNSYS Type 1 employing the second order collector performance equation is used to model the collectors. For the stationary collectors however, the standard single-order collector performance equation is used (a_2=0).

$$n = a_o K_{at} - a_1\left(\frac{\Delta T}{G}\right) - a_2\left(\frac{\Delta T^2}{G}\right) \qquad (1)$$

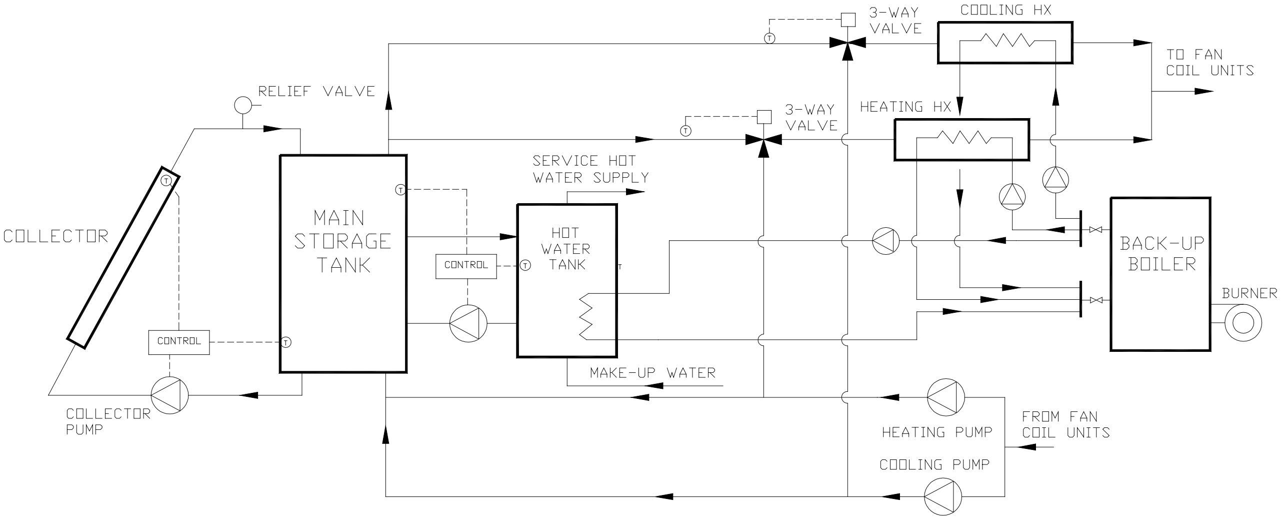


Fig. 7 Schematic diagram of the complete space heating, cooling and hot water system

It should be noted that for the single-order performance equation, if n is plotted against $\Delta T/G$ $[\Delta T=T_i-T_a]$ a straight line is obtained with intercept (a_o) and slope (a_1). The intercept depends on the optical properties of the collector whereas the slope depends on the collector heat loss coefficient. A high performance collector has a high a_0 value (close to unity) and a low the a_1 value, i.e., low heat losses. The values of a_0 and a_1 for the collectors considered in this work are shown in Tables 1 and 2.

The following model of incidence angle modifier is used in TRNSYS Type 1:

$$k_{at}=1-b_o\left(\frac{1}{\cos(q)}-1\right)-b_1\left(\frac{1}{\cos(q)}-1\right)^2 \quad (2)$$

For most of the stationary collectors considered only factor b_o is required (the values of b_0 are also shown in Tables 1 and 2). The useful energy extracted from the collectors is given by:

$$Q_u=F_RA\left[k_{at}(ta)G-U_L(T_i-T_a)\right] \quad (3)$$

The total useful energy for the whole year is obtained from:

$$Q_{u,a}=\sum_{d=1}^{365}\sum_{h=1}^{24}Q_u \quad (4)$$

and the annual auxiliary energy required, Q_{aux} is:

$$Q_{aux}=Q_{load}-\left\lfloor Q_{u,a}-Q_{loss}\right\rfloor \quad (5)$$

where Q_{loss} is the thermal losses from the storage tank, pipes and the relief valve.

As can be seen from the above equations the energy obtained from the solar collector field depends on the inlet temperature to the collector T_i, which depends on the thermal load and the thermal losses (Q_{loss}).

The specifications of the complete system are shown in Table 3. Water heated from solar energy is stored in a TRNSYS Type 4 stratified fluid storage tank. The vertical cylinder construction is made of copper and is thermally insulated with polyurethane. Also the tank is protected by a galvanised outer shell 0.6mm thick. A second smaller size tank is used as part of the domestic hot water subsystem. The size of this tank is 160 lt and is determined from the hot water consumption.

Although in practice one auxiliary boiler is used for satisfying the needs for auxiliary energy of all three subsystems, in the model three auxiliary heaters (TRNSYS Type 6) are used one for the DHW subsystem, one for the heating subsystem and one for the cooling subsystem set at an upper temperature of 50°C, 46°C and 93°C for the three subsystems respectively.

The LiBr-water absorption air conditioner (TRNSYS Type 7) is a single-effect unit, based on Arkla model WF-36. Its nominal capacity is taken as 65,000 kJ/hr, assuming no internal auxiliary heater and working in energy rate control.

Table 3 Specifications of the complete system

Parameter	Value
Collector area	Variable (m^2)
Main storage tank volume	Variable (m^3)
DHW storage tank volume	0.16 m^3
Solar differential thermostat ON	10°C
Solar differential thermostat OFF	2°C
DHW auxiliary heater	12,000 kJ/hr
DHW heater set temperature	50°C
Heating auxiliary heater	40,000 kJ/hr
Heating system heater set temp.	46°C
Cooling auxiliary heater	86,000 kJ/hr
Cooling system heater set temp.	93°C
DWH system pump capacity	200 kg/hr
Heating system pump capacity	1,195 kg/hr
Cooling system pump capacity	3,300 kg/hr
Absorption cooler capacity	52,000 kJ/hr

Although the hot water demand is subject to a high degree of variation from day to day and from consumer to consumer it is impractical to use anything but a repetitive load profile. This is not quite correct during the summer period, where the consumption pattern is somewhat higher. However, during this period, the temperature requirement for hot water is not as high as during winter. Consequently, the total thermal energy requirement is reasonably constant throughout the year. For the present simulation, the hot water consumption profile illustrated in Fig. 8 is employed, which assumes a daily hot water consumption of 120 litres at 50°C for a family of four (30 litres/person).

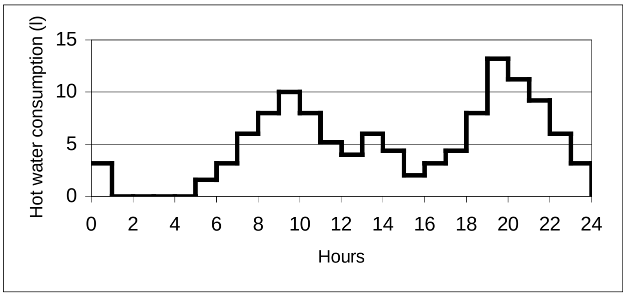


Fig. 8 Hot Water daily consumption profile

The system is simulated with TRNSYS using Typical Meteorological Year (TMY) data for Nicosia, Cyprus. TMY is defined as a year which sums up all the climatic information characterizing a period as long as the mean life of the system. The TMY for Cyprus was generated from hourly measurements, of solar irradiance (global and diffuse on horizontal surface, ambient temperature, wind speed and direction, and humidity ratio), for a seven-year period, from 1986 to 1992 using the Filkenstein – Schafer statistical method (Kalogirou, 2003). The measurements were recorded by the Cyprus Meteorological Service at Athalassa region, an area at the suburbs of the town of Nicosia. The TMY is considered as a representative year for the Cypriot and Mediterranean environment.

5.4 Economic Analysis Method Description

A life cycle analysis is performed in order to obtain the total cost (or life cycle cost) and the life cycle savings of the systems. The economic scenario used in this project is that 30% of the initial cost of the solar system is paid at the beginning and the rest is paid in equal instalments in 10 years. The period of economic analysis is taken as 20 years (life of the system), whereas the inflation rates of fuel and electricity, used for pumps, are mean values of the last 10 years in Cyprus. Maintenance and parasitic costs are also considered. Light fuel oil (LFO) is assumed to be used for a fuel-only system. From the addition of fuel savings incurred because of the use of the system and the tax savings the mortgage, maintenance and parasitic costs are subtracted and thus the annual solar savings of the system are estimated which are converted into present worth values of the system. These are added up to obtain the life cycle savings. The economic analysis can be performed either within the TRNSYS environment or in a spreadsheet program. For the present work, the spreadsheet application is used. A detailed description of the method of economic analysis of solar systems using spreadsheets is given in (Kalogirou, 1996).

Table 4 shows the estimated costs per square meter of the collectors and other economic parameters considered in the present analysis.

The investment cost of the stationary solar systems is estimated by from:

$$C_s = C_a A + C_v V \tag{6}$$

where C_a is the area dependent cost (€/m^2) and C_v is the volume dependent cost (€/m^3).

For the operation cost (C_o), maintenance and parasitic cost are considered. The former are estimated to be 1% of the initial investment and are assumed to increase at a rate of 0.5% per year of the system operation. The latter accounts for the energy required (electricity) to drive the solar pump. The total annual cost is given by:

$$C = C_s + C_o \tag{7}$$

It should be noted that the cost of the small domestic hot water system storage tank is not considered in the economic analysis as such a tank is present in the installation irrespective if the system is solar or not, thus only extra equipment is considered against the benefits obtained from the solar system.

Table 4 Investment cost of the collectors and other economic parameters considered in this study.

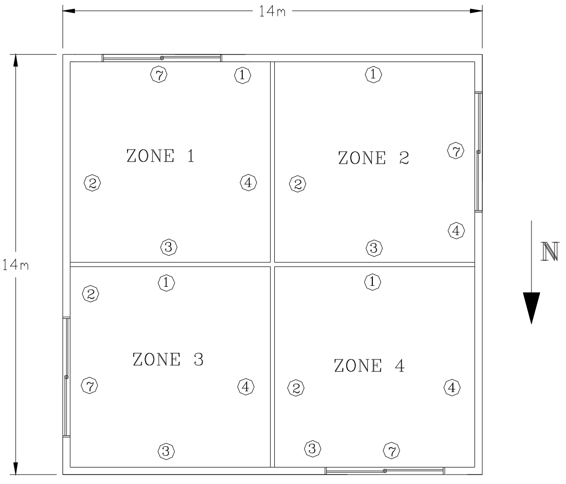
Collector type	Collector price (C_a)
FPC	187 €/m^2
AFP	204 €/m^2
ETC	425 €/m^2
Economic parameters	**Value**
Market discount rate	6.5%
Interest rate	5.2%
General inflation rate	4.5%
Conventional fuel price	0.6€/lt
Storage tank price (C_v)	1700 €/m^3
Notes**:** 1. Collector prices include collector mountings and field piping 2. Storage tank price includes also the cost of the solar pump	

6 Description of The Building

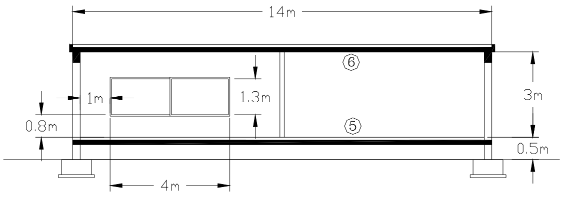
For the estimations carried out in this paper a model house is considered, as illustrated in Fig. 9. This is a typical house of 196m^2 floor area. The typical house consists of four identical external walls. Every wall is 14m in length by 3m in height and has a double glazing window of 5.2m^2. The typical house is constructed with double-walls made of 0.1m hollow brick and 0.02m plaster on each side and a layer of 0.05m insulation in between. The roof is constructed from fair-face 15cm heavy concrete, 5cm polystyrene insulation, 7cm screed and 0.4cm asphalt, covered with aluminum paint of 0.55 solar absorptivity. The model house is further divided into four identical zones and the partition walls are considered as walls separating the four zones.

For the present study TRNSYS Type 19 model is used to estimate the heating and cooling loads for a typical house by utilizing the transfer function method (TRNSYS, 2004). The transfer function method estimates the heating and cooling loads arising from walls, windows, flat roofs and floors. For every zone a separate TRNSYS Type 19 unit, is necessary. Details of the input parameters required to model the typical house are given in Florides *et al.* (2000).

Type 19 model has two basic modes of operation, i.e., the energy rate and the temperature level control modes. In the study the energy rate control mode is selected, since with this mode the temperature of the building can be maintained between specified limits and the energy required to maintain the zone in the specified temperature is given as output along with the limit temperature. The zone humidity ratio is also allowed to float between a maximum and a minimum limit specified by the user and the humidification or dehumidification energy is considered. A controller is used in conjunction with this mode to control the heating or cooling equipment.



PLAN VIEW



FLAT ROOF, TYPICAL SECTION

Fig. 9 Model house drawing

It is important to emphasize here that any attempt to apply solar heating or cooling in a house should be done only after the building is well insulated to reduce the thermal loads. The above construction results in the annual and hourly maximum thermal loads shown in Table 5. These are estimated by keeping the room temperature during wintertime to 21°C and during summertime to 25°C and the humidity ratio between 0.005 and 0.008 kg of water per kg of dry air. As can be seen the maximum thermal load is the cooling load. This is an expected result which agrees with the environmental conditions prevailing in Nicosia.

Table 5 Annual and hourly maximum thermal loads

Heating load		Cooling load	
Annual (GJ)	Maximum hourly (MJ/hr)	Annual (GJ)	Maximum hourly (MJ/hr)
12.03	39.61	79.38	87.37

7 Results

What is the ultimate objective of this kind of analysis is to determine the size and characteristics of the system which make the system viable and give the highest life cycle savings. In order to achieve this, the collector inclination, mass flow rate and area as well as the storage tank size needs to be optimized. Initially the optimization of the collector inclination and mass flow rate is presented.

7.1 Optimisation of the collector inclination

When a hot water only system is designed the usual inclination of the collector is latitude plus 5 degrees. However as the sun during summertime is higher on the sky than in wintertime and as a considerable amount of load needs to be covered during summertime as well for the solar cooling system an investigation needs to be carried out to determine the collectors' inclination which gives the smaller amount of total auxiliary energy. The total auxiliary energy is the addition of backup energy required to cover the heating, cooling and hot water loads. The results for the three types of collectors considered are shown in Table 6.

Table 6 Optimisation of the collector inclination

Collector	Slope (°)	Total auxiliary (GJ)	System f (%)
FPC	Lat-10°	82.57	14.81
	Lat-5°	**82.08**	**15.32**
	Lat	82.34	15.05
	Lat+5°	83.08	14.29
AFP	Lat-10°	61.38	36.68
	Lat-5°	**59.72**	**38.39**
	Lat	60.49	37.59
	Lat+5°	60.61	37.47
ETC	Lat-10°	24.97	74.24
	Lat-5°	**24.96**	**74.25**
	Lat	26.63	72.53

Notes: 1. For all cases $A=50m^2$, $V=2.5m^3$, Flow=54 $kg/hr\text{-}m^2$
2. f = solar contribution,
3. Bold cases show (optimum) values

As can be seen as the prevailing load is the cooling load, the optimum collector inclination obtained for all types of collectors is latitude minus 5 degrees, i.e., 30°, so as to have the collectors more perpendicular to the sun during summertime.

7.2 Optimisation of the collector flow rate

To find the optimum flow rate three combinations of collector and storage tank sizes were examined:

1. Collector area=$20m^2$, storage tank=$1.5m^3$

2. Collector area=40m^2, storage tank=2.0m^3
3. Collector area=60m^2, storage tank=2.5m^3

These combinations cover the whole range of collector area and storage tank volume that can be applied in the present system. The optimisation parameter is again the minimum auxiliary total energy (T_{aux}) required by the system to cover all loads (heating, cooling and hot water). The results are shown in Table 7. For these runs the optimum slope of the collectors obtained in previous section were used. Also to avoid having long lists of data only three values are presented for each case, the optimum (marked in bold) and the values immediate before and after the optimum.

Table 7 Collector flow rate optimisation

Collector	Area (m^2)	Tank (m^3)	Flow rate (kg/hr-m^2)	T_{aux} (GJ)
FPC	20	1.5	9	91.71
	20	1.5	**18**	**89.81**
	20	1.5	27	92.01
	40	2.0	9	80.79
	40	2.0	**18**	**77.90**
	40	2.0	27	78.77
	60	2.5	9	72.82
	60	2.5	**18**	**67.20**
	60	2.5	27	68.79
AFP	20	1.5	18	80.78
	20	1.5	**27**	**80.42**
	20	1.5	36	82.64
	40	2.0	18	59.16
	40	2.0	**27**	**59.13**
	40	2.0	36	61.63
	60	2.5	18	45.45
	60	2.5	**27**	**41.56**
	60	2.5	36	42.89
ETC	20	1.5	27	65.22
	20	1.5	**36**	**61.77**
	20	1.5	45	62.34
	40	2.0	27	33.30
	40	2.0	**36**	**31.06**
	40	2.0	45	32.00
	60	2.5	27	20.09
	60	2.5	**36**	**16.85**
	60	2.5	45	17.11

The optimum values are 18 kg/hr-m^2 for the FPC 27 kg/hr-m^2 for the AFP and 36 kg/hr-m^2 for the ETC. As can be seen a general guideline is that the poorer the collector characteristics the lower the flow rate required. It should be noted that all values obtained are much lower than the generally accepted value of 54 kg/hr-m^2, usually considered in solar systems. The obtained values are also cost effective as lower flow rate would require lower electrical power input.

7.3 Optimisation of the collector area and storage tank

The optimum size of collector area and storage tank size are determined from the economic analysis. The optimisation parameter is the life cycle savings (LCS), i.e., the optimum combination of these two parameters is required to be determined which maximises the LCS.

The results of this exercise are shown in Tables 8 and 9, namely Table 8 shows the performance parameters and Table 9 the economic parameters of optimum systems. As can be seen the advanced flat-plate collector (AFP) which has a good performance and a comparatively low cost requires a greater amount of collector area compared to the other collector types considered. The standard flat plate collector (FPC) is comparatively expensive for the energy it supplies as indicated by the low values of LCS. The evacuated tube collectors (ETC) although very expensive can find applications in environments with good solar potential, like Cyprus. In fact this type of collector gives the highest LCS. The contribution of the solar systems to cover the load of the various subsystems is represented by the solar contribution (f value). This contribution indicated is the percent of load covered (Q_{load}) with solar given by:

$$f = \frac{Q_{load} - Q_{aux}}{Q_{load}} \qquad (12)$$

Two such contributions are $f_{(HW)}$, the solar contribution for the hot water subsystem and $f_{(H)}$, the solar contribution for the heating subsystem. It is not possible to give a solar contribution value for the cooling subsystem as due to the COP of the single-effect absorption cooler which is of the order of 0.6 more thermal energy is required than the cooling load. Alternatively the total (annual) solar contribution $f_{(total)}$ is used, given by:

$$f_{total} = \frac{T_{load} - T_{aux}}{T_{load}} \qquad (13)$$

where T_{load} is the total annual load (heating + cooling + hot water load) and T_{aux} is the total auxiliary needed in one year.

To find the optimum systems shown in Table 8 require the investigation of a number combinations of collector areas and storage tank volumes. To show all the values obtained for the various collectors would require a lot of space and will not add more value to this paper. Therefore the results of only the best system are shown in Table 10.

As can be seen bigger systems with greater collector area and larger storage tank, although satisfy a large amount of the load are not viable, represented by the negative LCS. In this case negative LCS represent the money lost by installing and operating the solar system instead of satisfying the same demand with fuel. It seems that the cost of the storage tank plays also a very important role in this optimisation. This can be seen by comparing the performance of systems with the same collector but different storage tank volume. Additionally, the solar system satisfies almost all the hot water needs of the house, irrespective of the collector area.

Generally the greater the collector area the higher the useful energy collected (Q_u) and the lower the total annual auxiliary (T_{aux}) required to cover the load. Except for the case of hot water production, as more collectors are added more heating load is covered whereas the effect on cooling load is less as the cooling load is much bigger than the heating load.

8 Optimum System Performance

TRNSYS can give results on an hourly, daily, monthly and annual basis. So far the annual results were analysed. In this section the monthly performance of the optimum system is presented. This analysis can reveal the actual contribution of the solar collectors on a monthly basis.

The performance of the evacuated tube collector system (optimum system) is presented in Figs 10 and 11. Figure 10 shows the energy flows and Fig. 11 the solar contributions. As can be seen the useful energy supplied from the collectors is maximum during the summer months and the maximum value is during July and August with a value of about 11.3 GJ. Cooling load is also maximised during summertime and reaches a maximum value of 16.9 GJ during July. The cooling auxiliary energy is also maximised during summertime and the maximum value is reached during July and September and is about 7.9 GJ. During wintertime the energy supplied form the collectors satisfy a large amount of the heating needs of the house. The maximum heating auxiliary is required during January and is equal to 1.1 GJ. The only other months requiring heating auxiliary is February (0.61 GJ) and December (0.54 GJ). In all other months requiring heating load (March and November) this is satisfied completely by the solar system. The annual heating solar contribution as shown in Fig. 11 is 0.81 and the lowest value is in January and is equal to 0.75. Hot water is almost completely covered from solar energy. As can be seen from Fig. 11 both the monthly and the annual values are close to 1.

Table 8 Performance parameters of optimum systems

Collector	Area (m^2)	Storage tank (m^3)	Slope (°)	Flow rate (kg/h-m^2)	Qu (GJ)	Q_{aux-HW} (GJ)	$f_{(HW)}$ (%)	Q_{aux-H} (GJ)	$f_{(H)}$ (%)	Q_{aux-C} (GJ)	$f_{(total)}$ (%)
FPC	20	1.0	30	18	30.28	0.169	96.94	7.92	34.14	81.43	7.64
AFP	40	1.5	30	27	78.90	0.032	99.41	2.74	77.22	56.34	39.02
ETC	30	1.5	30	36	95.20	0.025	99.55	2.23	81.43	40.97	55.40

Table 9 Economic parameters of optimum systems

Collector	Area (m^2)	Storage tank (m^3)	T_{aux} (GJ)	FYFS (€)	LCS (€)
FPC	20	1.0	89.52	438.9	1757
AFP	40	1.5	59.11	924.7	3868
ETC	30	1.5	43.23	1178.3	5107

Table 10 Optimisation of evacuated tube collectors (ETC) [sample]

Area (m^2)	Storage tank (m^3)	Qu (GJ)	$f_{(HW)}$	$f_{(H)}$	T_{aux} (GJ)	$f_{(total)}$	FYFS (€)	LCS (€)
10	1.0	34.14	96.49	31.16	84.60	12.72	517.50	3025
20	1.0	65.06	99.13	67.71	61.61	36.44	884.67	4955
30	1.0	94.89	99.59	81.49	44.26	54.34	1161.83	5008
40	1.0	125.30	99.64	83.59	32.56	66.41	1348.83	4588
20	1.5	65.57	98.82	63.56	62.34	35.69	873.00	4143
30	**1.5**	**95.20**	**99.55**	**81.43**	**43.23**	**55.40**	**1178.33**	**5107**
40	1.5	125.30	99.63	85.54	31.15	67.87	1371.33	4312
20	2.0	65.60	98.68	63.95	62.74	35.27	866.67	3415
30	2.0	95.71	99.53	80.76	44.37	54.23	1160.17	4192
40	2.0	125.40	99.66	87.77	31.06	67.96	1372.67	3705
50	2.0	153.10	99.77	93.01	21.78	77.53	1521.00	2210
40	2.5	125.40	99.69	89.06	31.14	67.87	1371.50	3055
50	2.5	153.60	99.76	93.00	21.80	77.51	1520.67	1575
60	2.5	182.00	99.76	93.17	16.85	82.62	1599.67	-1002

The annual total contribution is equal to 0.55, the maximum value is in March and is equal to 0.78 and the minimum is in May and is equal to 0.46.

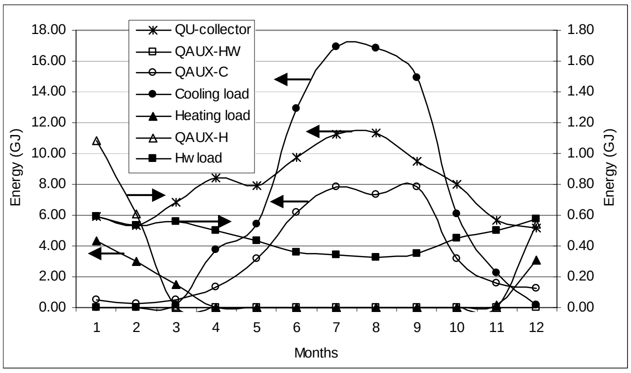


Fig. 10 Energy flows of the ETC system

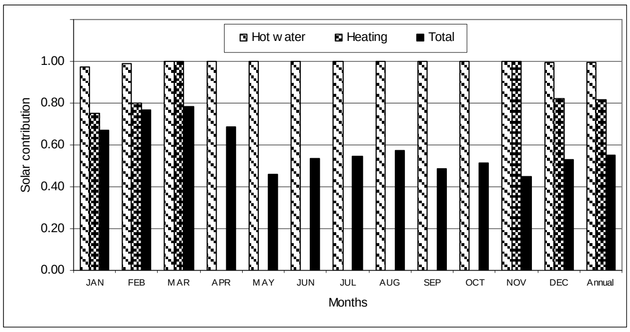


Fig. 11 Solar contribution of the ETC system

9 Conclusions

The design and performance of a complete solar space heating and cooling and hot water production system is presented in this paper. Solar cooling offers possibilities of using the same solar collectors for space cooling as well through an absorption chiller. To be viable solar space heating systems need to utilize a low temperature supply system. Absorption units on the other hand require temperature of the order of 90°C but the system during summertime is more effective and the available solar radiation is much more than the amount available during the wintertime. Additionally any effort in using solar energy for space heating and cooling must be done after the building is well insulated in order to reduce the thermal losses. Such a system need to be optimized with respect to the area of solar collectors and their inclination and the size of the storage tank. A system suitable for a typical 196 m^2 house is modelled and simulated with TRNSYS program for Nicosia, Cyprus. The results of these simulations show that a solar system employing evacuated tube collectors is the most viable. The system covers a considerable percentage of the heating, cooling and hot water loads of the building. The annual solar contribution is about 55%. The system covers completely the hot water load and about 81% of the heating load. The economic analysis performed showed that the system is viable as positive life cycle savings are obtained (5100 Euro). It can therefore be concluded that solar energy could be used for space heating, cooling and hot water production in houses.

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