Ianina Mofid
Louise Jivan Shah
Simon Furbo

Solar Heating Systems for Aizkraukle Secondary School no. 2

Theoretical Investigations

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Ianina Mofid
Louise Jivan Shah
Simon Furbo

Department of Civil Engineering
DTU-bygning 118
2800 Kgs. Lyngby
http://www.byg.dtu.dk

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II. PREFACE

The report describes results of calculations of the thermal performance of three solar heating systems for Aizkraukle secondary school no. 2 in Latvia: A solar domestic hot water system for the school including the sports facilities, a solar domestic hot water system for the kindergarten and a solar heating plant connected to the district heating network.

III. SUMMARY

The thermal performance of three different solar heating systems for Aizkraukle secondary school no. 2 in Latvia was calculated with simulation models. The systems are:

- A solar domestic hot water system for the school including the sports facilities.
- A solar domestic hot water system for the kindergarten.
- A solar heating plant connected to the district heating network.

The two solar domestic hot water systems are designed as low flow systems with a hot-water tank with a large thermal stratification. The heat is transferred from the solar collector loop to the domestic water by means of an external heat exchanger. Domestic water from the bottom of the hot-water tank is circulated to the external heat exchanger where the water is heated and back to the hot-water tank either through a fixed inlet or through a stratification inlet pipe securing that the water enters the tank in the "right" level. Simulations are carried out for both designs.

Further, the simulations are carried out for different hot-water consumption with different solar collector types and collector areas. The calculated thermal performance of the systems is a good basis to determine the design and dimensions of the systems, which will be built in Aizkraukle.

IV. RESUMÉ

Ydelsen af tre forskellige solvarmeanlæg til Aizkraukles Skole nr. 2 i Letland er beregnet. Det drejer sig om følgende anlæg:

- Et solvarmeanlæg til brugsvandsopvarmning til skolen og den nærved beliggende sportshal.
- Et solvarmeanlæg til brugsvandsopvarmning til skolens børnehave.
- En solvarmecentral til opvarmning af fjernvarmenettets returvand.

De to solvarmeanlæg til brugsvandsopvarmning udformes som low flow anlæg baseret på varmtvandsbeholdere med stor temperaturlagdeling. Varme overføres fra solfangervæsken til brugsvandet ved hjælp af en ekstern varmeveksler. Brugsvand føres fra bunden af beholderen frem til varmeveksleren, hvor solvarme overføres fra solfangervæske til brugsvand. Vandet føres retur til beholderen enten gennem et fast indløb eller igennem et stratifikationsindløbsrør, som sikrer at vandet tilføres beholderen i det ”rigtige” niveau, således at temperaturlagdelingen i beholderen bliver størst mulig. Begge beholderudformninger er taget i beregning.

Beregninger er gennemført for forskellige varmtvandsforbrug med forskellige solfangertyper og solfangerarealer. De beregnede anlægsydelser udgør et godt grundlag til at bestemme anlægsudformning og –størrelse for de solvarmeanlæg som skal opføres i Aizkraukle i efteråret 2002.

1 Introduction

It is under consideration to install three solar heating systems for Aizkraukle secondary school no. 2 in Latvia in the autumn of 2002: A solar domestic hot water system for the school including the sports facilities, a solar domestic hot water system for the kindergarten and a solar heating plant connected to the district heating network.

Schematic illustrations of the three systems are shown in figures 1, 2 and 3. The solar heating system for the school and the kindergarten are designed as low flow systems as described in [1]. The solar heating plant consists of a number of solar collector panels and a heat exchanger.

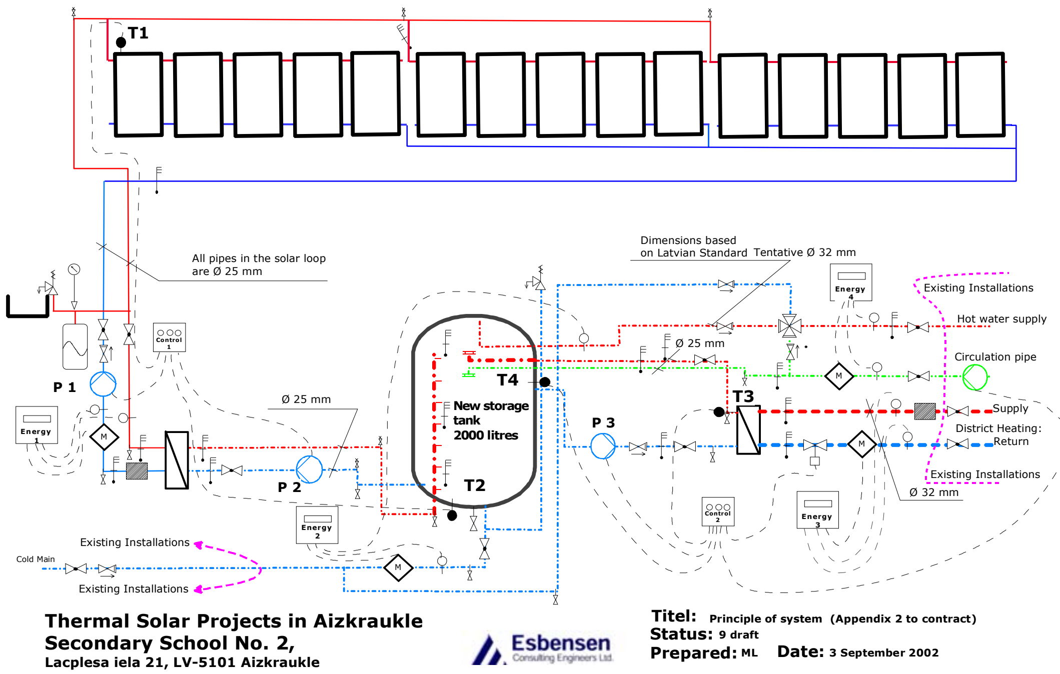

Figure 1: Schematic illustration of the solar heating system for the school.

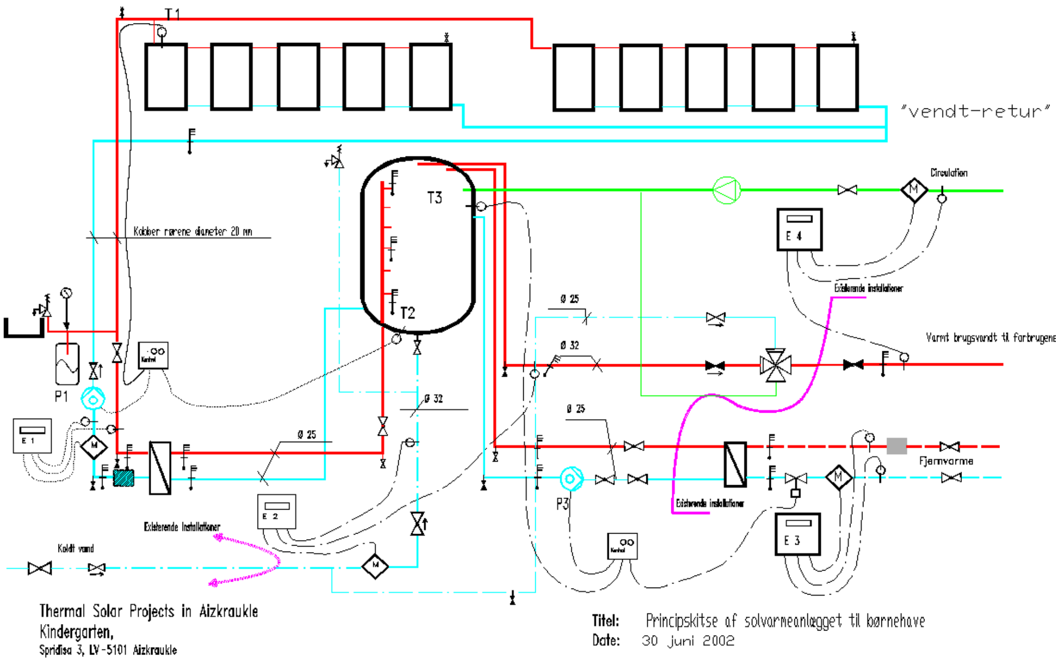

Figure 2: Schematic illustration of the solar heating system for the kindergarten.

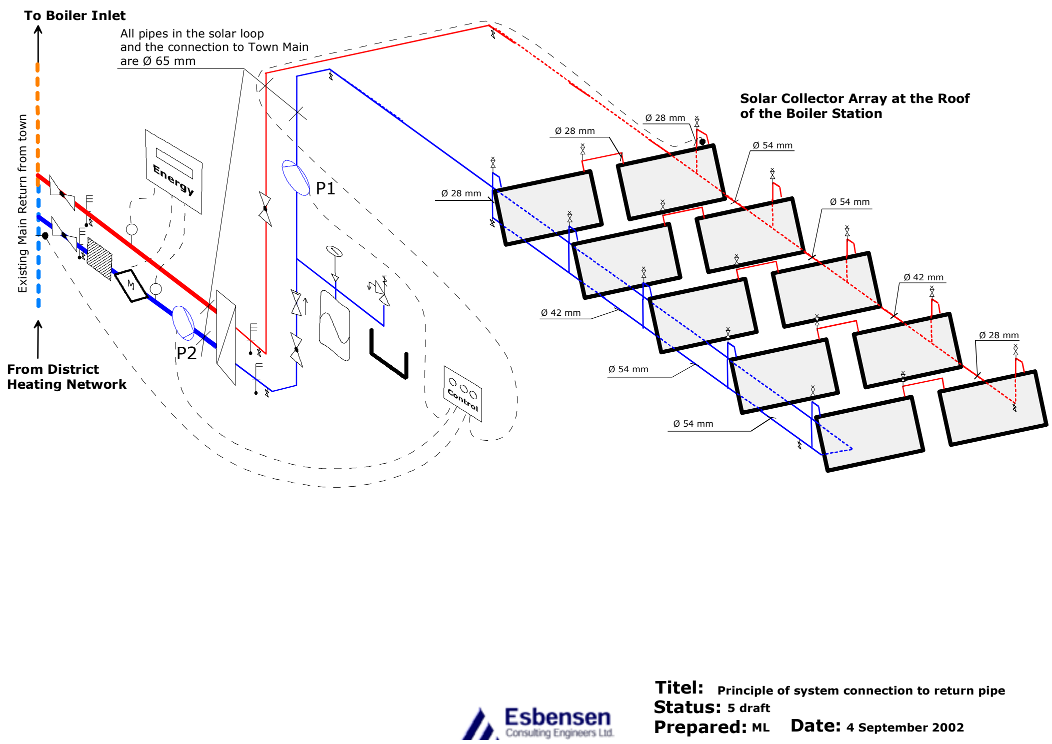

Figure 3: Schematic illustration of the solar heating system of the solar heating plant.

1.1 School

At the school, solar heating will be used for heating the domestic water, which, among other things, is to be used in the bathing facilities at the sports centre and in the canteen. The predominant hot-water consumption will be for the showers in the changing rooms at the sports centre. It is assumed that the daily hot-water consumption is about 800 litres in the canteen. In connection with sports activities there is a consumption of hot water at weekends. The total hot-water consumption at the school is expected to be about 2-3 m^3 per day, it was therefore suggested to establish the solar heating system based on 40-60 m^2 solar collectors.

Calculations are made for both 40 and 60 m^2 solar collectors. The city architect had decided that the solar collectors should be placed on the roof. The school has a flat roof with enough room for 60 m^2 solar collectors. The solar collectors will be mounted on racks and be facing south with a tilt angle of 40°.

1.2 Kindergarten

At the kindergarten, where there are 10 groups of 10 children, i.e. 100 children in all, the solar heating will also be used for heating the domestic water. There is a kitchen, a bathroom with 5 washbasins, and a shower cabinet for each group of children. The main part of the hot domestic water is used for washing-up.
There was great uncertainty as regards the expected consumption, so in February 2002, two meters were installed: one on the cold-water side and one on the hot-water side. The measurements showed a hot-water consumption between 3 and 6 m^3 per day on weekdays. The kindergarten is closed at weekends. The first time round calculations were carried out with 40 and 60 m^2 solar collectors with a daily consumption varying between 3 and 6 m^3.

It turned out that there is no room for such a large system. Further, it is assumed that going over washing-up routines, hot-water savings could be obtained e.g. by using dishwashers. Therefore calculations are carried out with daily consumptions varying between 2 and 4 m^3 and with 20 and 40 m^2 solar collectors, respectively. At the kindergarten there are hardly other options than to place solar collectors on the roof. The building has a flat roof, too, where solar collectors will be mounted on a rack with a tilt angle of 40°, facing south.

1.3 District heating system

Aizkraukle's local district heating supplies the consumers (incl. the school and the kindergarten) with domestic hot water and hot water for space heating. As a rule, district heating systems in Latvia are closed systems with an inlet pipe and an outlet pipe. It has been stated that the inlet temperature is about 90°C in the winter period and about 70°C in the summer period, whereas the outlet temperature is about 70°C in the winter period and about 45°C in the summer period. The temperature level of Aizkraukle's district heating system is shown in figure 4.

During a visit to the district heating station it turned out that it is possible to place about 5-6 rows of 25 m^2 solar collectors on the flat roof of the station, i.e. about 125-150 m^2 solar collectors. The solar heating plant is to be integrated into a district heating system by connecting the solar collectors via a heat exchanger to the return loop with no form of storage, i.e. without a storage tank. In that way the solar heating plant will heat the water from the return loop before the water is led to the boiler, which results in a reduced fuel consumption. Thus, solar energy can be utilized at the lowest possible temperature.

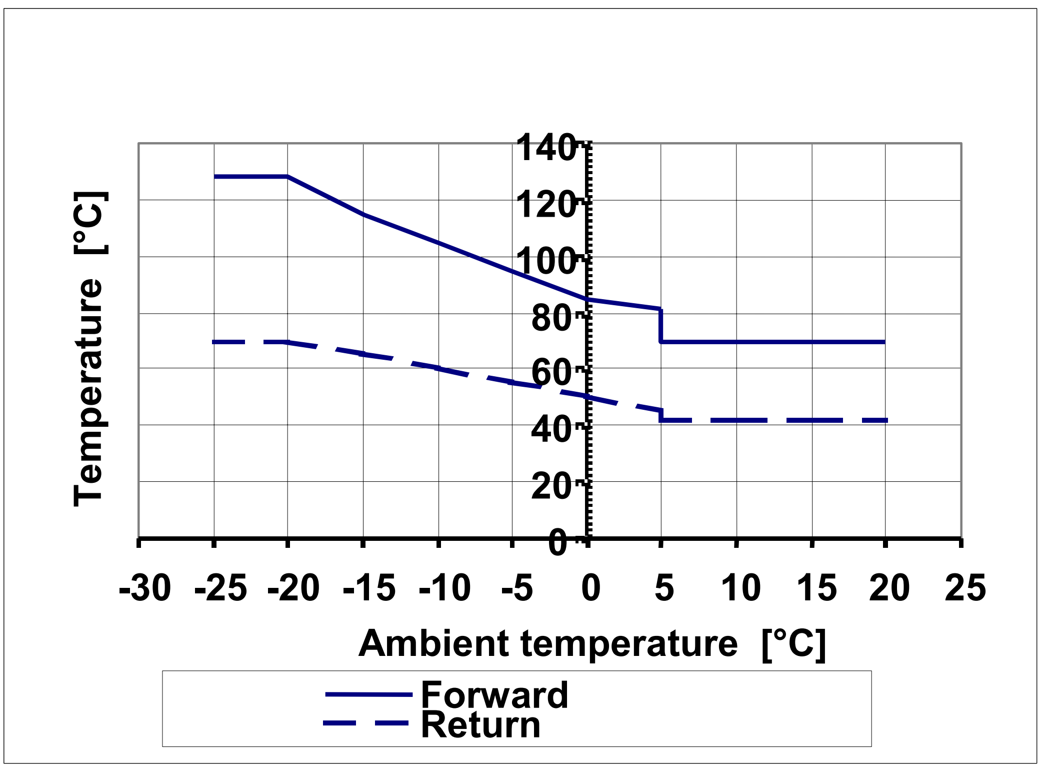

Figure 4: Temperature level for Aizkraukle's district heating system.

2 Calculation assumptions for the school and the kindergarten

2.1 Model description

The simulation program TRNSYS was used to calculate the performance of the solar heating systems. The program is suitable for detailed analyses of energy systems. TRNSYS consists of 9 separate programs with different functions. One of them is a graphic pre-processor, PRESIM, which permits the construction of one's own model by connecting graphically different components, and at the same time gives full mathematical specifications of the model. By means of the program PRESIM an input file is established, which is read by TRNSYS to run the simulations.

An example of a fundamental model, which was built in PRESIM for the school/kindergarten, is shown in figure 5. Each component has a TYPE number in PRESIM's library and is much more than a graphic symbol. By double-clicking on each component, a window appears where the properties of the component are described in the form of input data, output data, and parameters. In that way, a mathematical model of each component of the system is formed.

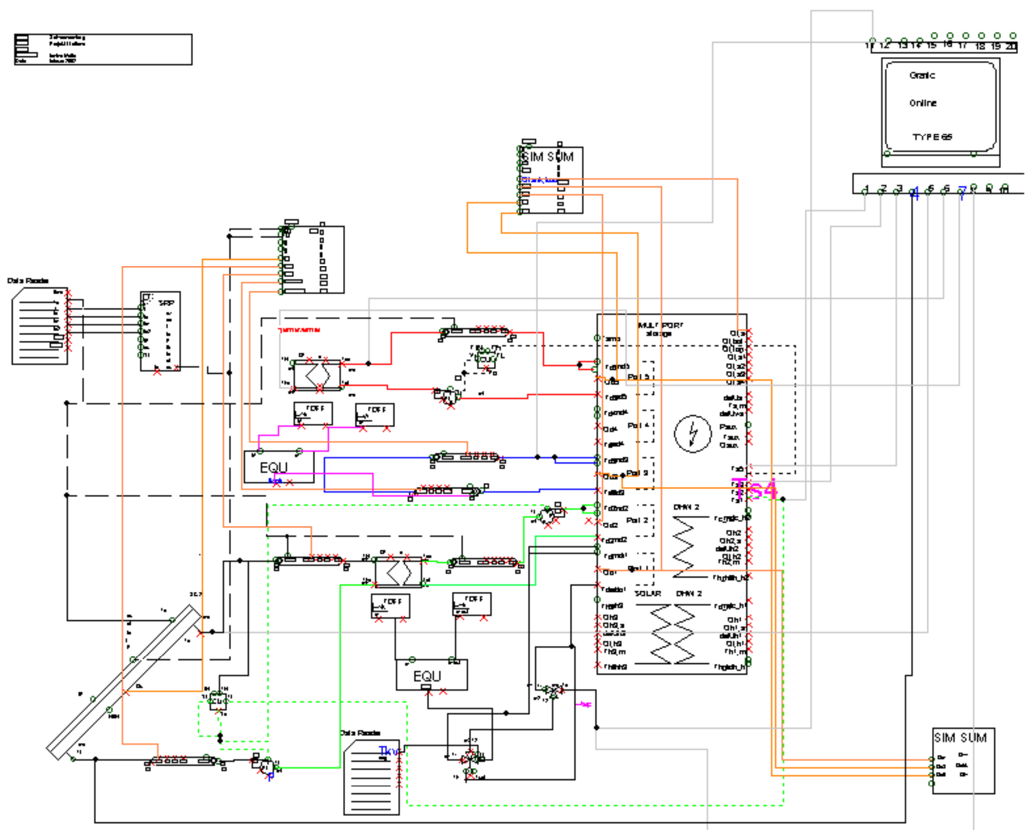

Figure 5: Example of the model built in PRESIM.

2.2 Weather data

To calculate the performance of the solar heating system, it is necessary to know weather data of the place where the solar collectors are to be placed. The Test Reference Year developed in [2] is used in the calculations.

2.3 Cold water temperature

The temperature of cold water that is supplied to the tank varies in the course of the year. As a starting point, the variation of the cold-water temperature for Denmark [3] is taken. However, 2 K colder temperatures are used. The variation of the cold-water temperature for Latvia during the year is illustrated in figure 6.

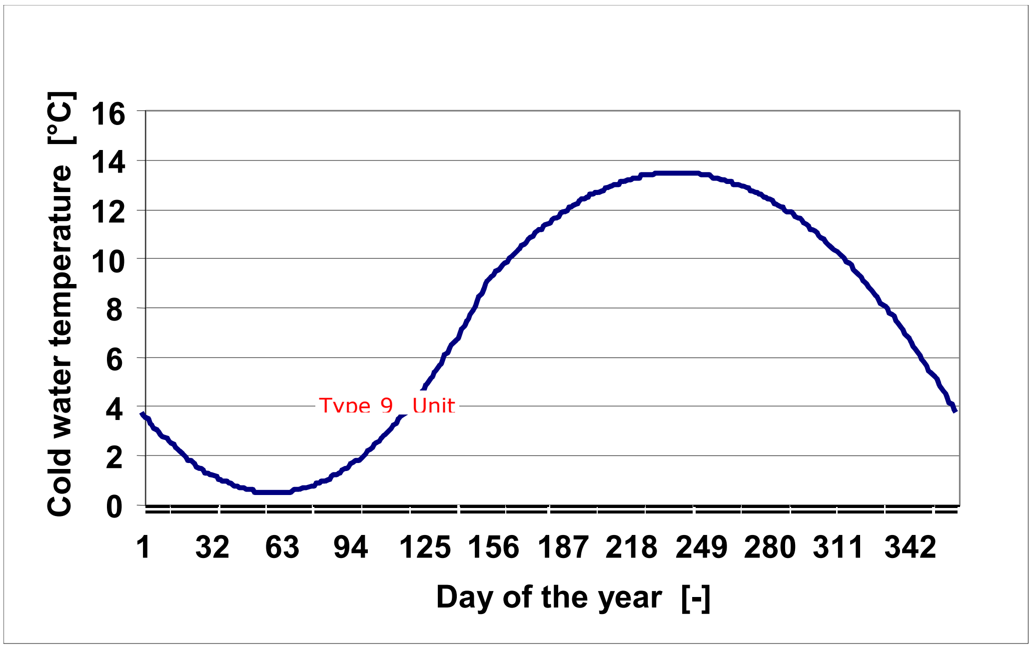

Figure 6: Cold-water temperature for Latvia during the year.

2.4 Tapping profiles

There is no information on consumption pattern, either for the school or the kindergarten. A consumption pattern of the school is estimated from the fact that the daily consumption of the school is about 2000-3000 l, and the portion of the canteen is about 800 l per day. There is, however, great uncertainty with regard to the hot-water consumption for the bathing facilities at the sports centre, so calculations have been made with both 2 and 3 m^3 per day**.** Estimated consumption pattern of the school is shown in figure 7.

To begin with, calculations for the kindergarten were made with hot water consumption of 3, 4, 5, and 6 m^3 per day, as the measurements have shown that the hot-water consumption is between 3 and 6 m^3 per day. Further, calculations were carried out with consumption volumes of 2 m^3 per day. Estimated consumption patterns for the kindergarten are shown in figures 8-12.

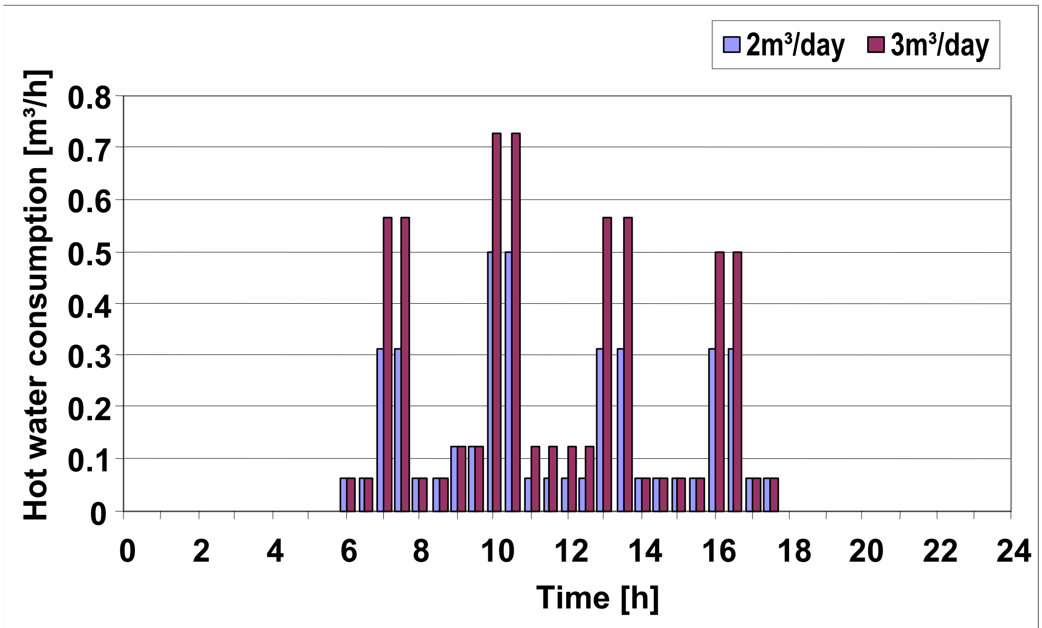

Figure 7: Consumption pattern of the school.

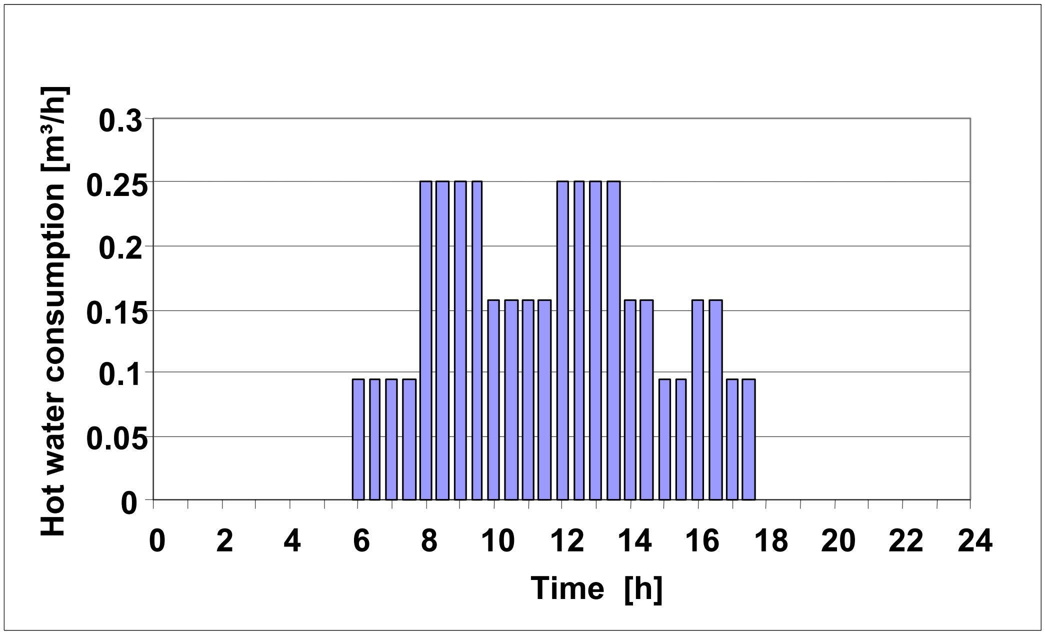

Figure 8: Consumption pattern of the kindergarten for the consumption volume 2 m^3/day.

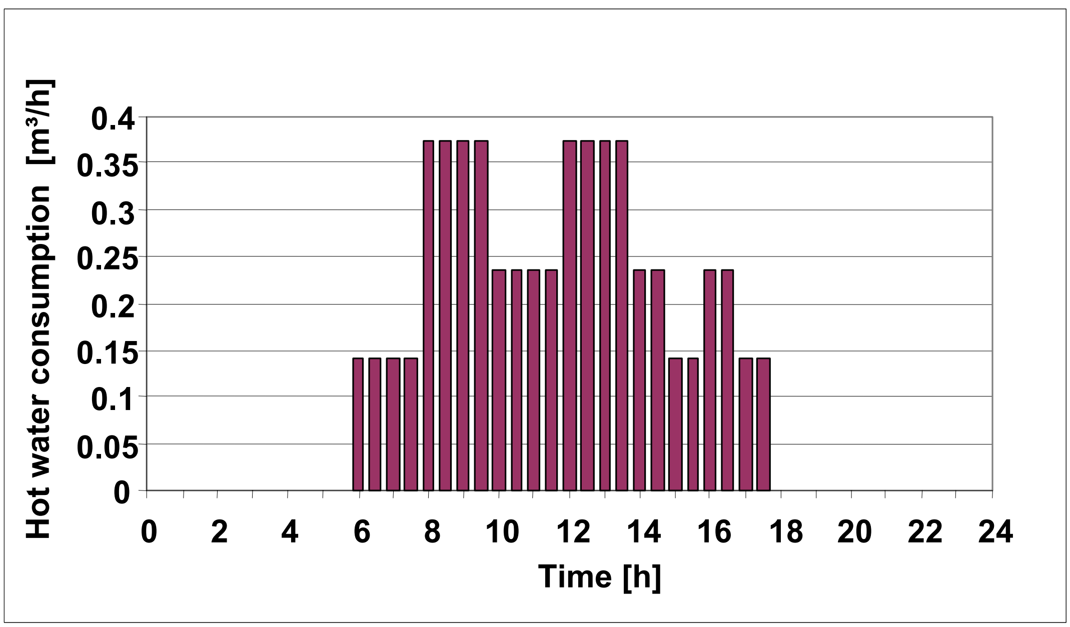

Figure 9: Consumption pattern of the kindergarten for the consumption volume 3 m^3/day.

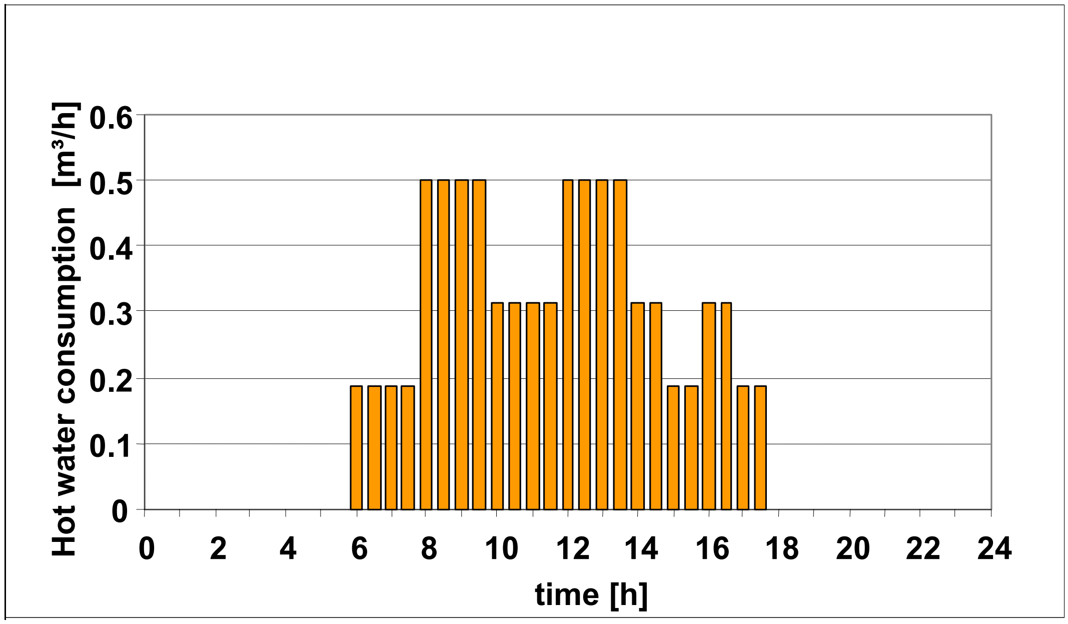

Figure 10: Consumption pattern of the kindergarten for the consumption volume 4 m^3/day.

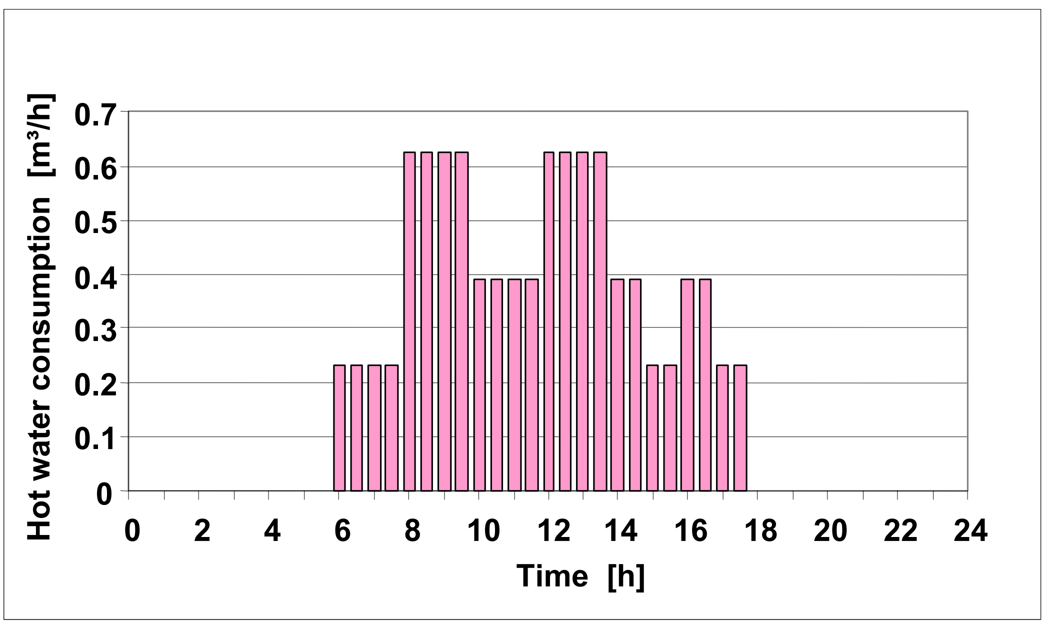

Figure 11: Consumption pattern of the kindergarten for the consumption volume 5 m^3/day.

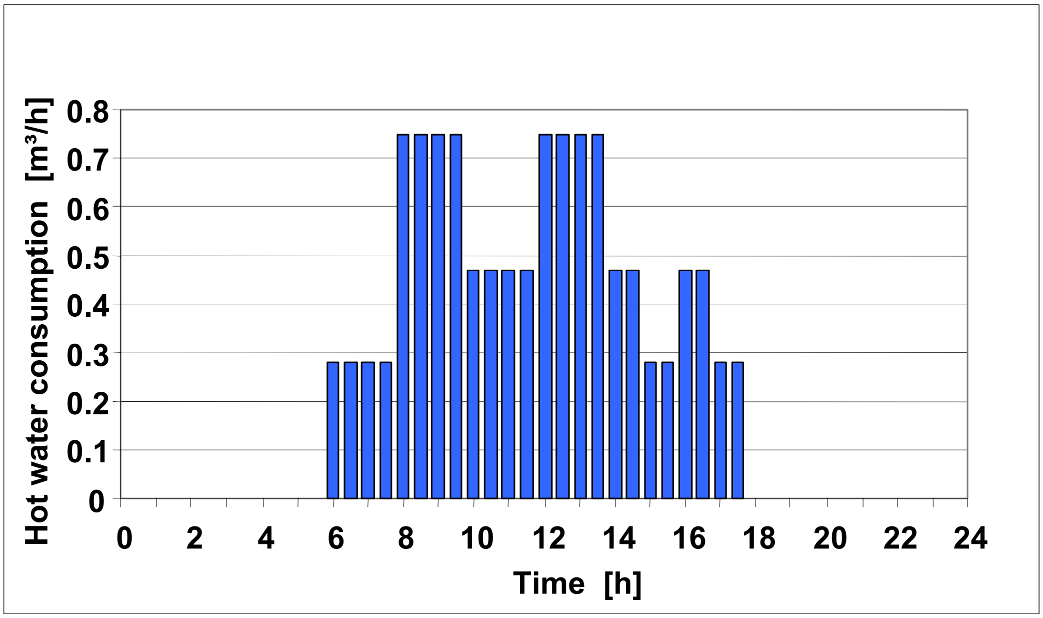

Figure 12: Consumption pattern of the kindergarten for the consumption volume 6 m^3/day.

2.5 Solar collector loop

For each system calculations were carried out with four different solar collectors:

- HT (produced by ARCON Solvarme A/S)
- HT new (improved version of HT)
- BA30 (produced by BATEC A/S)
- Batec-Marstal, type BA 120T (produced by BATEC A/S in co-operation with Marstal VVS A/S).

The efficiency for low incidence angles for BA30 is $\eta=0.756-4.37\cdot(T_m-T_a)/G-0.010\cdot(T_m-T_a)^2/G$ and the incidence angle modifier is: $k_\theta=1-\tan^{3.8}(\theta/2)$, [4].

The efficiency for low incidence angles for BA 120T is: $\eta=0.773-2.48\cdot(T_m-T_a)/G-0.016\cdot(T_m-T_a)^2/G$.

The incidence angle modifier for BA 120T at $\theta=50°$ is: $k_{50°}=0.92$, [5].

The old and the new version of HT solar collector were tested at DTU. The old HT solar collector had the following efficiency at low incidence angles: $\eta=0.75-3.00\cdot(T_m-T_a)/G-0.065\cdot(T_m-T_a)^2/G$. The incidence angle modifier is: $k_\theta = 1-\tan^{3.0}(\theta/2)$.

The new improved version of the HT solar collector (with transparent area $12.53m^2$) was tested at DTU, and the efficiency for low incidence angles is: $\eta = 0.81-2.11\ (T_m-T_a)/G-0.0077\ (T_m-T_a)^2/G$. The incidence angle modifier is: $k_\theta = 1-\tan^{3.4}(\theta/2)$

By comparing the efficiency expressions of the four solar collectors, see figure 13, it appears that the new HT solar collector is considerably better than the old one and the best solar collector as regards efficiency.

Data for different solar collectors are keyed into the program by means of the component, Type 1, see figure 5, which symbolizes the solar collector.

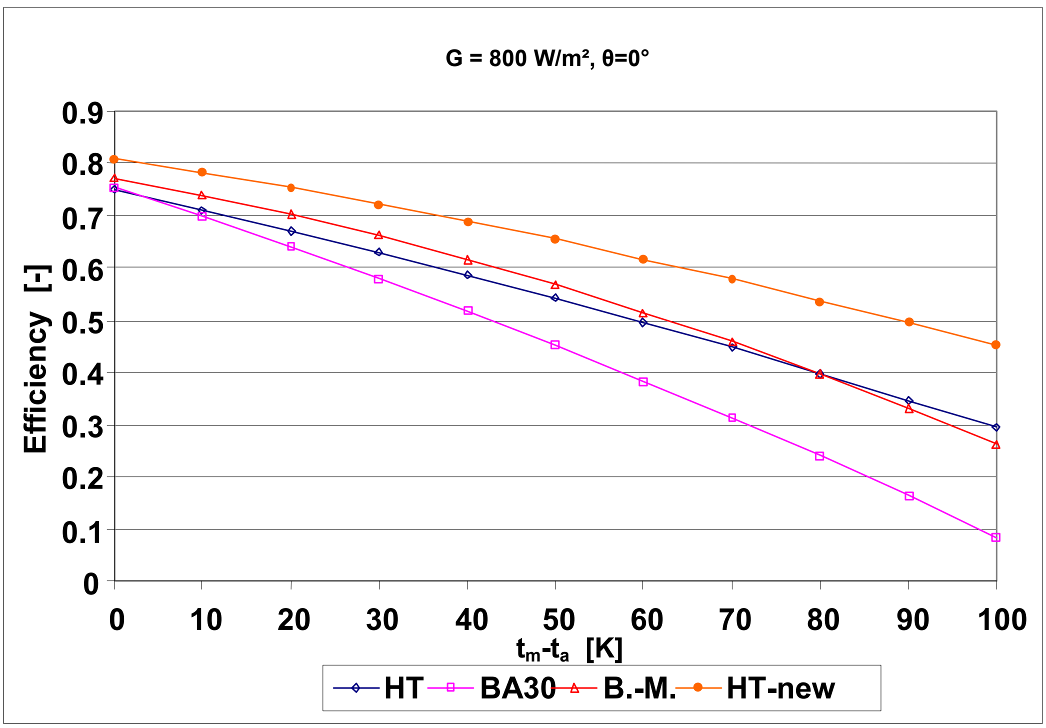

Figure 13: The efficiency of solar collectors as a function of difference between the mean temperature of the solar collector fluid and the ambient temperature.

The solar heating systems are designed as low-flow systems, where the solar collector fluid in the solar collector loop circulates very slowly through the solar collectors with a volume flow rate of about 0.2 l/min. per m^2. Such a slow flow in the solar collector loop will result in a large increase of temperature through the solar collectors. As solar collector fluid a 45% propylene glycol/water-mixture is used to make the solar collectors safe from frost. The solar collector loop is equipped with an external plate heat exchanger, where solar energy is transferred to the domestic water. A plate heat exchanger is the type of heat exchanger that has the greatest heat exchange capacity rate compared to the volume of the heat exchanger.

Mantle tanks are almost never used for large solar collectors, as the heat transfer area between the mantle and the domestic water would be too small to transfer the solar energy from a large solar collector field.

Spiral tanks have a relatively high heat exchange capacity rate, but sometimes there is not enough space in the tank for all the spirals, and eventually there will be problems with lime removal.

2.6 Tank

The heat storage of the solar heating system is of great importance for the thermal performance of the solar heating system; therefore, a well-dimensioned storage with the largest possible thermal stratification is greatly to be preferred. An advantageous thermal stratification in the storage is a precondition of obtaining the largest possible performance of the solar heating system. The low temperatures at the bottom of the tank guarantee a high performance of the solar collector because the fluid in the solar collectors is cooled to a lower temperature, by which the solar collector efficiency increases. The high temperatures at the top of the tank guarantee that the heat is immediately usable and that the energy supply from the auxiliary energy supply system is reduced. To get the largest possible thermal stratification the tank should be tall and thin, so that the joint surface between heat and cold has the smallest possible area.

At rising temperatures the water expands and gets a lower density. Gradually, as the water gets hotter it will go upwards, and accordingly cold water, which is heavier, will move downwards in the tank. That particular property of the water makes it possible to build up a large thermal stratification in the storage. Another important property of the water is its relatively low thermal conductivity, which causes the heat to spread downwards very slowly.

It is very important to ensure that no mixing arises because of the water that is led into the tank, as that would spoil the thermal stratification. Therefore the water must be tapped from or supplied to the tank very carefully. Furthermore, the thermal conduction in the water and in the tank material, and also the heat loss will contribute to reduce temperature differences.

The upper part of the storage is heated via the external heat exchanger of the district heating system to keep the temperature at the top of the storage at 55°C. Cold water is supplied at the bottom of the storage and hot domestic water is tapped from the top of the storage. The solar collector loop heats the lower part of the tank. The outlet position to the district heating system and the inlet position from the solar collector loop are determined with different solar collectors, solar collector areas, tank sizes and consumption patterns by means of a large number of simulations in TRNSYS. Data for the tank in the program are established by means of the component Type 140, see figure 5.

2.6.1 Tank size

If you want to store a great amount of heat from a time when the sun is shining to a time when the water is to be used, it is logical to install a large tank. On the other hand it is difficult with a large tank to ensure that cold water at the bottom and hot water at the top will not mix in the long run. Furthermore, there is a risk of flowering of bacteria if the water stays in the tank for too long a time.

On account of the above, the tank size must correspond to the consumption. Experience from solar heating systems in Denmark has shown that the optimum volume of hot-water tanks should be about 50 l per m^2 solar collector.

At the school the storage tank is placed in the basement where there is enough space for a 2 m high tank with a volume of maximum 2500 litres.

At the kindergarten the storage tank is placed in a recess in the laundry on the ground floor, just above the group heating station in the basement where there is room for a 2 m high storage tank of 1500 to 2000 litres. Here it is possible to place the external heat exchanger of the solar collector loop under the tank and thus establish thermosyphoning of the domestic water. There are two advantages with the thermosyphoning. Firstly, it is not necessary to install a pump in order to pump the domestic water through the heat exchanger of the solar collector loop. Thus the energy for the pump is saved. Secondly, thermosyphoning of the domestic water will result in a larger thermal stratification in the tank.

2.6.2 Inlet design

There are four fluid flows through the storage: From solar collector loop, from auxiliary heating, from tapping and from circulation pipe. To some extent, all these four fluid flows can create mixing and destroy the thermal stratification in the tank. Naturally, the inlet design and size of the storage are important for the extent of the mixing. Therefore, the inlets from these loops to the storage must be designed very carefully, so that the flow rate at the inlet does not become too large. A larger inlet dimension and storage cause less mixing in the storage.

2.7 District heating system

If the temperature at the top of the tank becomes lower than 55°C, the domestic water circulates from the upper part of the tank through the external heat exchanger of the district heating system. The size of the volume that is heated by means of district heating is dimensioned from knowledge of consumption and simulated by means of TRNSYS. The district heating loop in figure 5 is indicated by a red colour.

2.8 Circulation pipe

The domestic hot water system must be kept heated so that it will always be possible to tap hot water. To avoid waste of water it must always be possible within 10 seconds to tap hot water at a temperature of minimum 50°C at the most distant tapping location. The heat loss from the pipes results in the domestic water having to circulate by means of a circulation pump. For both the school and the kindergarten the volume flow rate in the circulation loop is presumed to be 700 l/h. The circulation loop in figure 5 is indicated by a blue colour.

2.9 Control

All components of the solar heating system can be controlled according to two different control principles:

- differential control
- time control.

The differential control measures the temperature two places in the system, at low and high temperatures, respectively. This control is for instance used in the solar collector loop and for the auxiliary heating of domestic water. When the difference of temperature between high and low is larger than the initial difference, the pump in the solar collector loop or in the district heating system is started and it is stopped when the stop difference is reached. Data for control of the district heating loop and the solar collector loop are established in the program by means of controlling the components Type 2 Unit 1 and Type 2 Unit 2, respectively, in figure 5.

The time control is carried out at fixed hours during the day. This control is for instance used in the tapping loop and the circulation loop. The control of the circulation loop is made according to the principle of time, i.e. it is turned on for 6 or 12 hours a day. Data for the control system of the circulation loop are formed by means of controls, as shown in figure 5 as the component Type 14 Unit 2.

In sunny summer periods with small hot-water consumption, situations may occur when the temperature of the solar collector fluid in the solar collector loop rises and there is a risk of boiling. To avoid boiling the control system must ensure that the temperature of the domestic water in the storage tank does not get higher than 75°C. That is possible by starting the pump of the district heating system to transfer the heat from the domestic water to district heating.

3 Calculation of the thermal performance for the solar heating systems for the school and for the kindergarten.

By means of the simulation program TRNSYS a large number of calculations were carried out for the school and the kindergarten. These calculations form the basis of the design of the solar heating system. It is clear that the design of the solar heating system is decisive for its performance. The purpose of the large number of simulations was to illustrate how the storage volume and the storage design and also the choice of solar collector type will influence the thermal performance of the solar heating system. Further it was also important to find out how the changes in consumption patterns will influence the thermal performance of the solar heating system.

As mentioned above, an input file is first to be established in a graphic processor PRESIM to run simulations in TRNSYS. In PRESIM, graphic as well as mathematical specifications of the model are formed. By connecting different components a graphic model of the system is built, and a mathematical description is made by keying in input data and parameters for all the components.

Below, data input for the school and the kindergarten is described.

3.1 Data input to the school.

3.1.1 Solar collector type.

Defined by means of component Type 1. Calculations are carried out with 4 different solar collectors.

All solar collectors are facing south with a tilt angle of 45°. Data input for solar collectors appear from tables 1-4. For the school, calculations are made with about 40 m^2 or 60 m^2 solar collectors.

Para-meter	Specifications	Unit	Value
2	Number of solar collectors	-	3/5
3	Total transparent area	m^2	37.6/62.5
4	Thermal capacity of the solar collector fluid	kJ/kg*K	3.8
7	Start efficiency	-	0.75
8	1st order heat loss coefficient	W/m^2*K	3.0
9	2nd order heat loss coefficient	W/m^2*K^2	0.0065
13	1st order incidence angle modifier from ASHRAE*	-	-0.25
14	2nd order incidence angle modifier from ASHRAE*	-	0.42

Table 1: Parameters for HT solar collector.

* The incidence angle modifier is calculated somewhat different in ASHRAE and has the form $K_{\alpha\tau} = 1 - \beta_0 (S) - \beta_1 (S)^2$,
where
β_0 is 1st order incidence angle modifier from ASHRAE,
β_1 is 2.order incidence angle modifier from ASHRAE.
By comparing the expressions $K_\theta = 1 - \tan^a(\theta/2)$ and $K_{\alpha\tau} = 1 - \beta_0 (S) - \beta_1 (S)^2$ approximate values for β_0 and β_1 can be found.

Para-meter	Specifications	Unit	Value
2	Number of solar collectors	-	13/20
3	Total transparent area	m^2	39/60
4	Thermal capacity of the solar collector fluid	kJ/kg*K	3.8
7	Start efficiency	-	0.756
8	1st order heat loss coefficient	W/m^2*K	4.37
9	2nd order heat loss coefficient	W/m^2*K^2	0.01
13	1st order incidence angle modifier from ASHRAE*	-	-0.2
14	2nd order incidence angle modifier from ASHRAE*	-	0.35

Table 2: Parameters for BA30 solar collector.

Para meter numb er	Specifications	Unit	Value
2	Number of solar collectors	-	3/5
3	Total transparent area	m^2	35.82/59.7
4	Thermal capacity of the solar collector fluid	kJ/kg*K	3.8
7	Start efficiency	-	0.773
8	1st order heat loss coefficient	W/m^2*K	2.48
9	2nd order heat loss coefficient	W/m^2*K^2	0.016
13	1st order incidence angle modifier from ASHRAE*	-	-0.11
14	2nd order incidence angle modifier from ASHRAE*	-	0.25

Table 3: Parameters for Batec-Marstal solar collector.

Para-meter	Specifications	Unit	Value
2	Number of solar collectors	-	3/5
3	Total transparent area	m^2	37.6/62.5
4	Thermal capacity of the solar collector fluid	kJ/kg*K	3.8
7	Start efficiency	-	0.81
8	1st order heat loss coefficient	W/m^2*K	2.11
9	2nd order heat loss coefficient	W/m^2*K^2	0.0077
13	1st order incidence angle modifier from ASHRAE*	-	-0.1
14	2nd order incidence angle modifier from ASHRAE*	-	0.25

Table 4: Parameters for the new HT solar collector.

3.1.2 The tank.

For the school, 4 different storage volumes are calculated. A tank made of ordinary steel and insulated with 100 mm mineral wool with a thermal conductivity of 0.045 W/(m·K) is taken as a starting point. The basement of the school is 2.9 m high, so there is room for a storage tank about 2 m high.

The upper part of the storage is heated via the external heat exchanger of the district heating system to keep the temperature at the top at 55°C. On the one hand, the volume that is heated by the auxiliary energy supply system must be as small as possible, but on the other hand there must be enough domestic hot water to meet the consumption. The necessary auxiliary volume is found by means of parameter variations in Trnsys (the parameter 30 ”fvout” in table 7), and that volume is of course different from one tapping profile to another, but independent of the tank size:

For the tapping profiles 3 m^3 for 7 days and 3 m^3 for 5 days +1.5 m^3 for 2 days the auxiliary volume must be about 600 l (at a volume flow rate of the domestic water through the external heat exchanger of the district heating system of 1400 l/h).
For the tapping profiles 2 m^3 for 7 days and 2 m^3 for 5 days +1.0 m^3 for 2 days the auxiliary volume must be about 200 l (at a volume flow rate of the domestic water through the external heat exchanger of the district heating system of 1200 l/h). The outlet position to the district heating loop for different tapping profiles expressed as the relative height of the tank appears from table 5 (0 – the bottom and 1- the top). The tank is always 2 m high.

The parameter (”sens4” in table 7) indicates the place of the temperature sensor for control of the district heating system. Its position is somewhat higher than the outlet to the district heating loop.

Tapping profile / Tank size	3 m^3 for 7 days and 3 m^3 for 5 days+1.5 m^3 for 2 days **(600 l)**	2 m^3 for 7 days and 2 m^3 for 5 days+1.0 m^3 for 2 days **(200 l)**
2500 l	0.76	0.92
2000 l	0.7	0.9
1500 l	0.6	0.87
1000 l	0.4	0.8

Table 5: The outlet to the district heating loop (stated as relative height of the tank).

Solar heat is transferred to the lower part of the tank, where the temperature of the water is lower, so that it is possible to transfer heat from solar collectors at a low temperature. Through parameter variations in TRNSYS (the parameter 20 ”sfind” in table 7) the level is found where a permanent inlet from the solar collector loop should be connected so that the performance becomes as high as possible. It is important to lead the solar heat into the tank at a right temperature level so that the thermal stratification is not destroyed. It is clear that the best fixed inlet position from the solar collector loop (and thus the performance of the solar heating system) depends on the solar collector area, the tapping profile, the tank size, and the size of the volume heated by the auxiliary energy supply system. The inlet position from the solar collector loop that results in the highest system performance for different tapping profiles, solar collector areas, and tank sizes appears from table 6, where the inlet position is stated as a relative height of the tank (0 – the bottom and 1- the top).

The disadvantage of the fixed inlet from the solar collector loop is that solar heat is not always transferred to the ”right” level in the heat storage, by which the thermal stratification is destroyed. In periods with high solar collector fluid temperatures the solar heat should be transferred to the upper part of the storage, in periods with solar collector fluid temperatures of average height the solar heat should be transferred to the middle part of the storage, and with relatively low solar collector fluid temperatures the solar heat should be transferred to the lower part of the storage.

If the thermal performance of the solar heating system is heavily dependent on the thermal stratification in the heat storage tank, the so-called stratification inlet pipes should be used. This guarantees that the water is transferred to the tank at the ”right” level so that the thermal stratification in the tank becomes as large as possible.

Figure 14 illustrates how the thermal performance of the solar heating system depends on the inlet position from the solar collector loop. It appears that in this case (37.5 m^2 solar collector, 2000 l storage and a consumption of 3

m^3/day) it is possible to increase the performance by about 3.2% by installing stratification inlet pipes. In cases with larger solar collector areas and less consumption it is possible to increase the performance by up to 7.5% by using stratification inlet pipes, as shown in figure 15.

Tapping profile / Tank size	3 m^3 for 7 days and 3 m^3 for 5 days+1.5 m^3 for 2 days		2 m^3 for 7 days and 2 m^3 for 5 days+1.0 m^3 for 2 days	
Approximate solar collector area	40 m^2	60 m^2	40 m^2	60 m^2
2500 l	0.5/1250 l	0.5/1250 l	0.6/1500 l	0.5/1250 l
2000 l	0.5/1000 l	0.5/1000 l	0.6/1500 l	0.5/1000 l
1500 l	0.5/750 l	0.4/ 600 l	0.6/1500 l	0.5/750 l
1000 l	0.3/300 l	0.3/ 300 l	0.6/1500 l	0.5/500 l

Table 6: The best inlet position from the solar collector loop (stated as relative height of the tank).

Para-meter	Specifications	Unit	Value
1	The height of the tank	m	2
2	The volume of the tank	m^3	1.0/1.5/2.0/2.5
3	The thermal capacity of the fluid	kJ/kg-K	4.18
4	The density of the fluid	Kg/m^3	1000
7	Initial temperature	^{0}C	10
8	Heat loss from the bottom	W/K	10.4
9	Heat loss from the top	W/K	0.57
11	Heat loss from the sides	W/K	3.5
17	Relative height of the inlet for cold water supply (domestic water loop)	-	0
18	Relative height of the outlet for tapping of the domestic hot water	-	1
20	Relative height of the inlet from the solar collector loop	-	**sfind**
21	Relative height of the outlet to the solar collector loop	-	0
22	Stratified inlet from the solar collector loop? (yes=1)	-	0/1
23	Relative height of the inlet from the	-	**ckind**

	circulation pipe loop		
24	Relative height of the outlet to the circulation pipe loop	-	1
25	Stratified inlet from the circulation pipe loop? (yes=1)	-	0
29	Relative height of the inlet from the district heating system loop	-	0.99
30	Relative height of the outlet to the district heating system loop	-	**fvout**
31	Stratified inlet from the district heating system loop (yes=1)	-	0
32	Relative position of the 1st temperature sensor (the bottom)	-	0
33	Relative position of the 4th temperature sensor	-	**sens4**
79	Number of temperature layers in the tank	-	300

Table 7: Parameters for the tank.

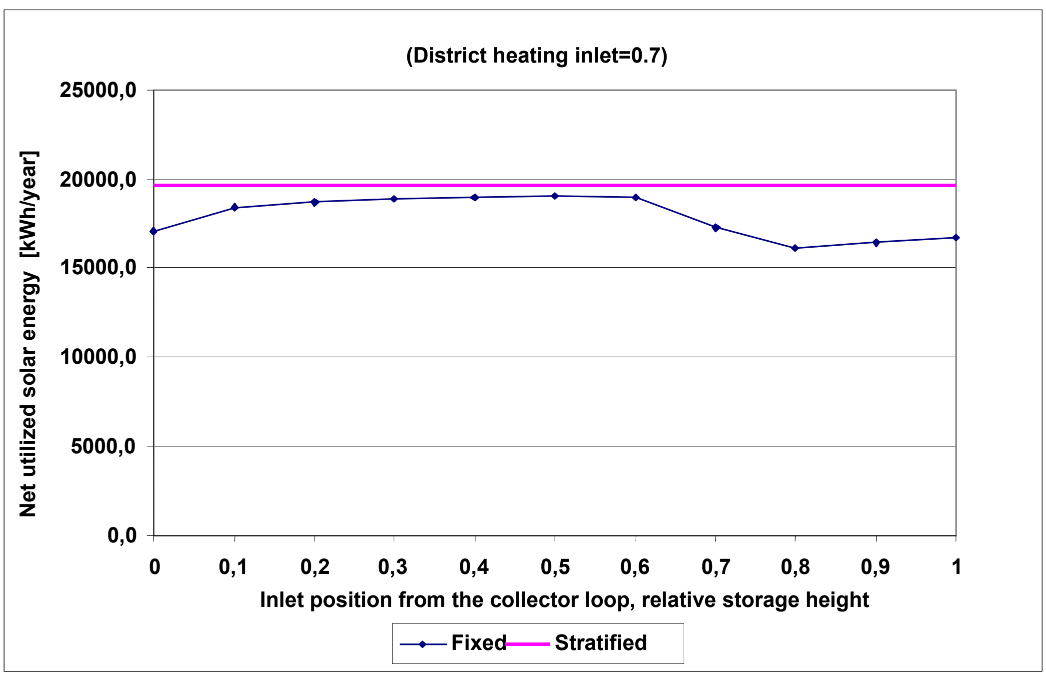

Figure 14: The thermal performance of the solar heating system as a function of the inlet position from the solar collector loop with about 40 m^2 solar collector area and a tapping profile of 3 m^3 for 7 days.

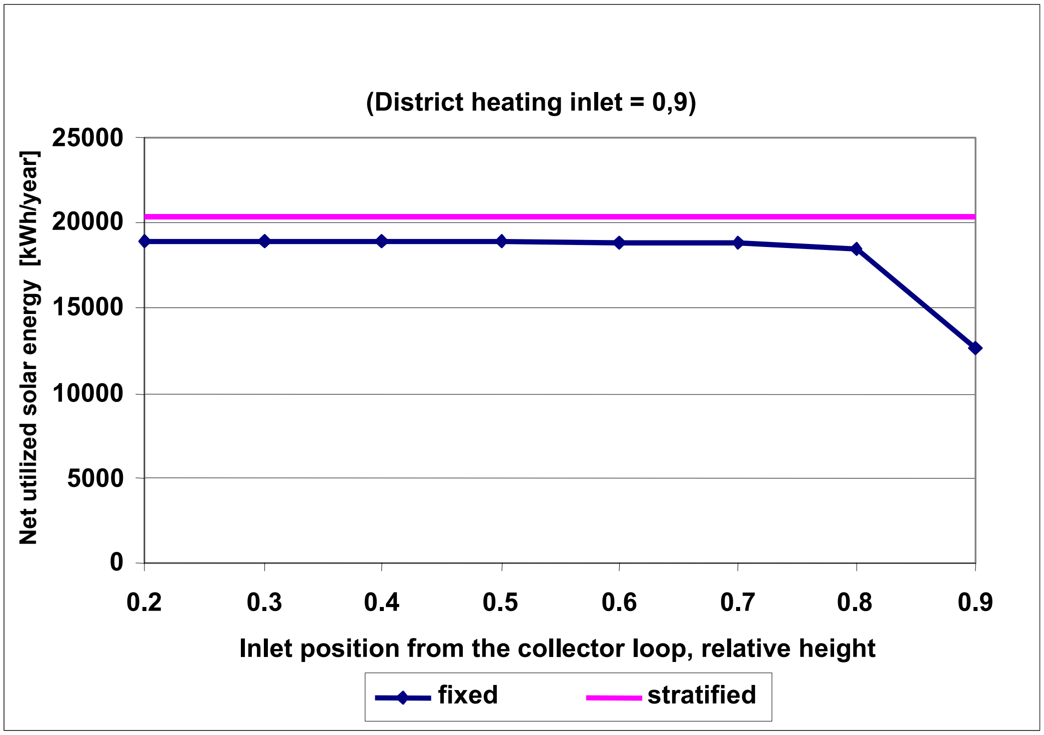

Figure 15: The performance of the solar heating system as a function of the inlet position from the solar collector loop with about 60 m^2 solar collector area and a tapping profile of 2 m^3 for 5 days+1.0 m^3 for 2 days.

3.1.3 Control of the solar heating system

The solar collector loop and the district heating loop are controlled according to the difference principle, i.e. according to the temperature difference. Here a two-position form of control is used (the so-called on/off-control). Controls generate a control function, which can have a value of either 0 or 1, as shown in figure 16.

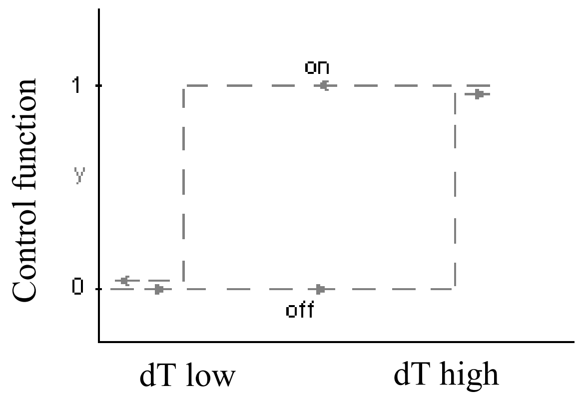

Figure 16: Control function.

The temperature of the tank is measured at a level somewhat higher than the outlet to the district heating system. The temperature at the top of the tank is to be kept at 55°C. If this temperature exceeds 57°C, i.e. if the difference between the desired tapping temperature (set-up temperature) and the temperature that is measured in the tank gets higher than 2 K, the pump is stopped. The pump starts again when the temperature at the top of the tank falls below 55°C.

To control the solar collector loop, two temperature sensors are to be installed: One of them is to measure the temperature in the solar collectors, and the other is to measure the temperature at the bottom of the tank. When the temperature in the solar collectors gets 5 K higher than the temperature at the bottom of the tank, a pump starts circulating solar collector fluid in the solar collector loop and at the same time the other pump starts circulating the domestic water in the heat exchange loop. The pumps are stopped when the temperature difference between the solar collectors and the bottom of the tank gets smaller than 2 K.

The circulation pump is controlled according to the principle of time, i.e. it is turned on for 6 or 12 hours a day. It is clear that the circulation pump should not operate for a long time if it is not necessary as this results in heat loss from the pipes and, in addition to that, extra energy consumption for the pump. On the other hand the comfort of the consumers should be considered and waste of water avoided, as according to Danish standards the consumers shall be able to tap the hot water at a water flow of 0.2 l/s 10 seconds after the tapping has been started, at the latest.

3.1.4 Heat exchanger

As appears from the sketch of the system of the school there are two heat exchangers: One of them belongs to the district heating system and the other to the solar collector loop. By using the two heat exchangers, it is possible to build a large thermal stratification in the heat layer and by this guarantee a high performance of the solar heating system.

As external heat exchanger in the solar heating system, usually a counter flow plate heat exchanger is used. The advantages of the plate heat exchanger are among others flexibility, high efficiency, and a compact structure. It is easy to clean, and having plates of stainless steel it is suitable for corrosive fluids.

The heat exchange capacity rate for the heat exchanger of the district heating system is calculated by means of the MS-DOS program HEX1, which is based on the so-called ε, N_{tu} –method (Number of Transfer Unit) [6]. Here a balanced counter flow heat exchanger is taken as a starting point, i.e. the thermal capacity flows of the cold side and the hot side are identical: $(m \cdot c_p)_c = (m \cdot c_p)_k$. Data input for this component appear from tables 8 and 9.

Para-meter	Label	Specifications	Unit	Value
1	Thi	The inlet temperature of the hot side	°C	70
2	mh	The mass flow rate of the hot side	kg/h	1300
3	Tci	The inlet temperature of the cold side	°C	*
4	mc	The mass flow rate of the cold side	kg/h	**

Table 8: Input data to the external heat exchanger of the district heating system.

* changed with each time step

** The mass flow rate of the cold side depends on the consumer profile: with 3 m^3 for 7 days or 3 m^3 for 5 days+1.5 m^3 for 2 days m_c= 1400 kg/h and with 2 m^3 for 7 days or 2 m^3 for 5 days+1.5 m^3 for 2 days m_c= 1200 kg/h.

Para-meter	Specifications	Unit	Value
1	Flow arrangement	Counterflow	-
2	Heat exchange capacity rate	W/K	5000

Table 9: Parameter for the external heat exchanger of the district heating system.

In the solar collector loop normally a counter flow heat exchanger is used, for which the heat exchange capacity rate is assumed to be 50 W/K per m^2 solar collector. Data input for this heat exchanger is formed by means of the component Type 5 Unit 2 and appears from tables 10 and 11.

Parameter	Label	Specifications	Unit	Value
1	Thi	The inlet temperature of the hot sides	˚C	*
2	mh	The mass flow rate of the hot sides	kg/h	**
3	Tci	The inlet temperature of the cold sides	˚C	*
4	mc	The mass flow rate of the cold sides	kg/h	**

Table 10: Input data for the external heat exchanger of the solar collector loop.

* The temperatures are changed with each time step.

** The system is designed as a low-flow system, where the solar collector fluid in the solar collector loop circulates with a volume flow rate of about 0.2 l/min. per m^2 solar collector. Therefore the mass flow rate of the hot side is calculated with different solar collector areas in each case:

$$0.2\left[{}^{l}\!\big/_{\text{min. per m}^2}\right]*10^{-3}\left[{}^{m^3}\!\big/_{l}\right]*1018\left[{}^{kg}\!\big/_{m^3}\right]*60\left[{}^{min}\!\big/_{h}\right]*\text{the solar collector area}\left[m^2\right]$$

Here a balanced heat exchanger is allowed for, for which reason the mass flow rate of the cold side equals the mass flow rate of the hot side.

Para-meter	Specifications	Unit	Value
1	Flow arrangement	Counter flow	-
2	Heat exchange capacity rate	W/K	***

Table 11: Parameters for the external heat exchanger of the solar collector loop.

*** The heat exchange capacity rate is calculated for each case with different solar collector areas: *50 [W/K per m^2] * the solar collector area [m^2].*

3.2 The thermal performance of the solar heating system for the school.

3.2.1 Choice of the storage volume.

Calculations were carried out for different solar collectors with four storage volumes: 1000 l, 1500 l, 2000 l, and 2500 l with fixed as well as stratified inlet from the solar collector loop. Calculations are made with four different tapping profiles to elucidate the influence of the consumption pattern on the thermal performance of the solar heating system:

- 3 m^3 on weekdays and no consumption at weekends,
- 3 m^3 on weekdays plus half consumption (1.5 m^3) at weekends,
- 2 m^3 on weekdays and no consumption at weekends and
- 2 m^3 on weekdays plus half consumption (1.0 m^3) at weekends.

Figures 17-23 show the net utilised solar energy of the solar heating system with different solar collectors as a function of the storage volume. The calculations for the school are carried out with about 40 m^2 and 60 m^2 solar collectors. For each tapping profile the auxiliary volume, heated by the district heating system, is kept constant, whereas the best inlet position from the solar collector loop for different storage volumes is found by means of the simulations. The net utilised solar energy is shown both for the best placed fixed inlet from the solar collector loop and for an inlet indicated with dimensions where stratification pipes are used, and so that the domestic water is transferred to the storage at the ”right” level. The net utilised solar energy is defined as the size of the hot-water consumption plus the heat loss of the circulation pipe minus the heat that is transferred to the system from the district heating system.

From figures 17-23 it appears that the larger the storage volume, the greater the thermal performance of the solar heating system becomes. Further it appears that the larger the consumption, the greater the thermal performance of the solar heating system becomes. It is clear that the solar heating system with more solar collectors will yield more.

The storage volume of the solar heating system for the school with either about 40 m^2 or 60 m^2 solar collectors should not be smaller than 2000 l.

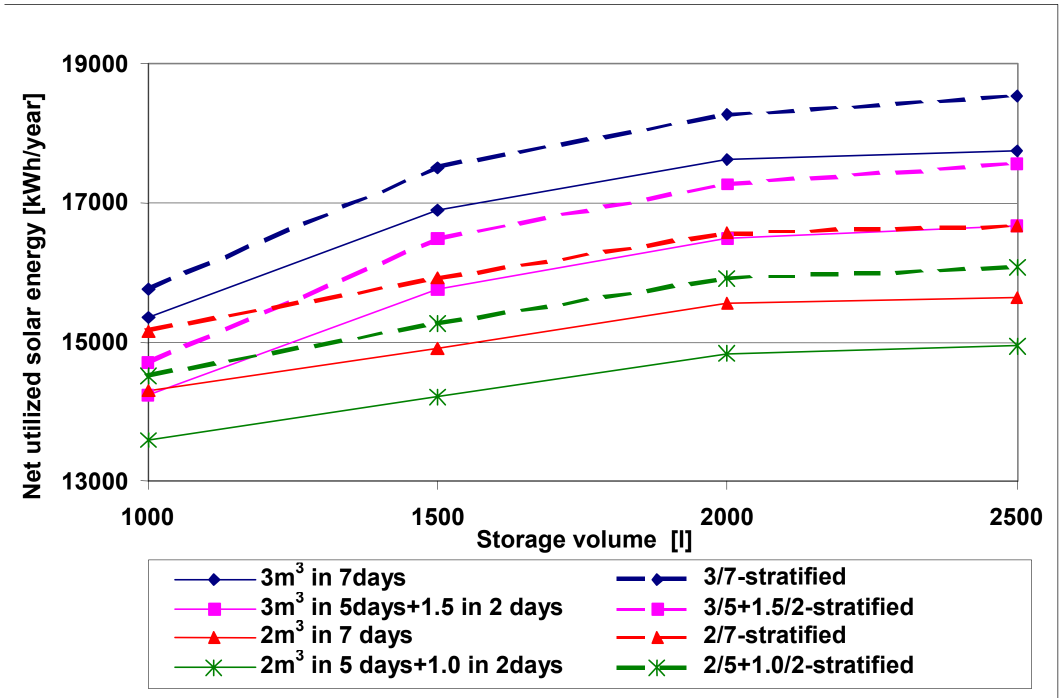

Figure 17: Net utilized solar energy as a function of the storage volume for the system with a 37.5 m^2 HT solar collector.

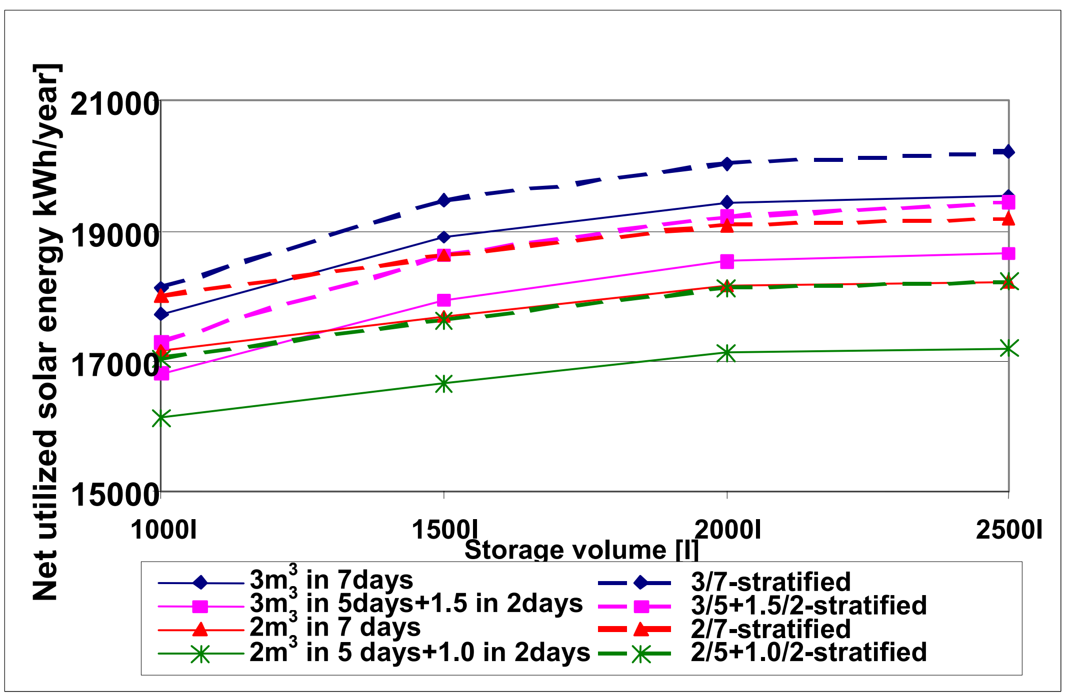

Figure 18: Net utilized solar energy as a function of the storage volume for the system with a 35.82 m^2 Batec-Marstal solar collector.

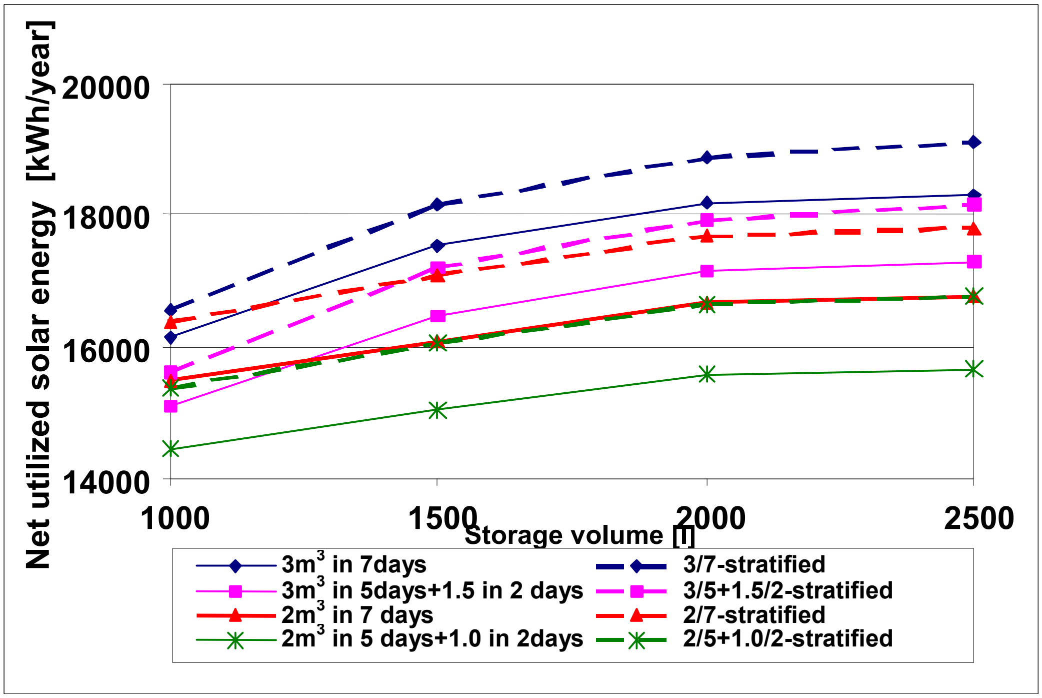

Figure 19: Net utilized solar energy as a function of the storage volume for the system with a 39 m^2 BA 30 solar collector.

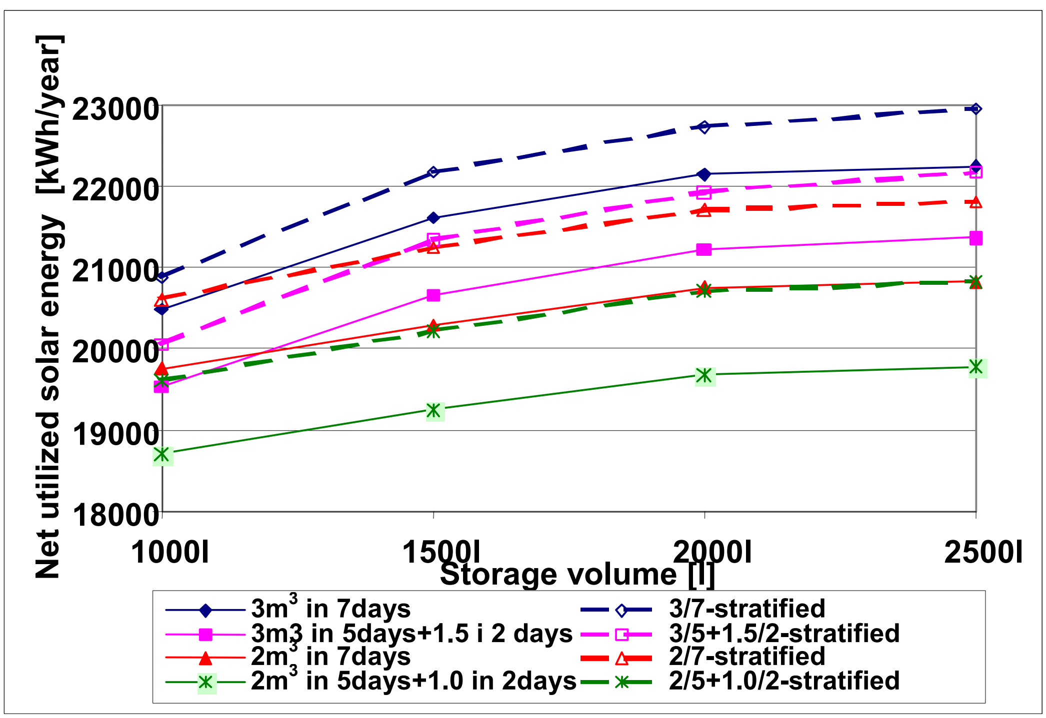

Figure 20: Net utilized solar energy as a function of the storage volume for the system with a 37.5m^2 HT-new solar collector.

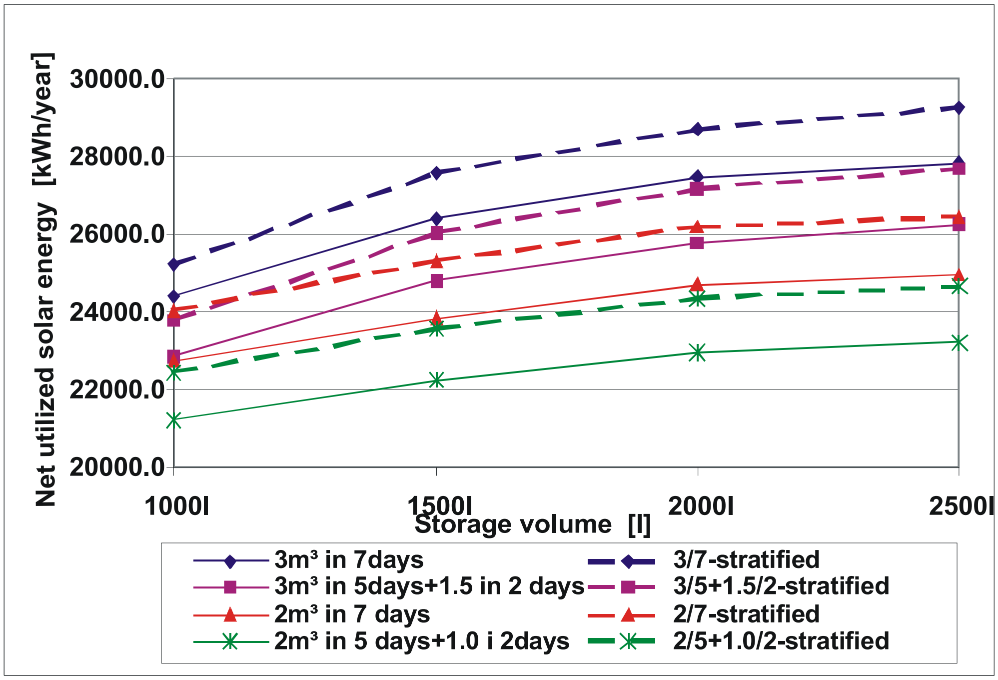

Figure 21: Net utilized solar energy as a function of the storage volume for the system with a 62.5 m^2 HT solar collector.

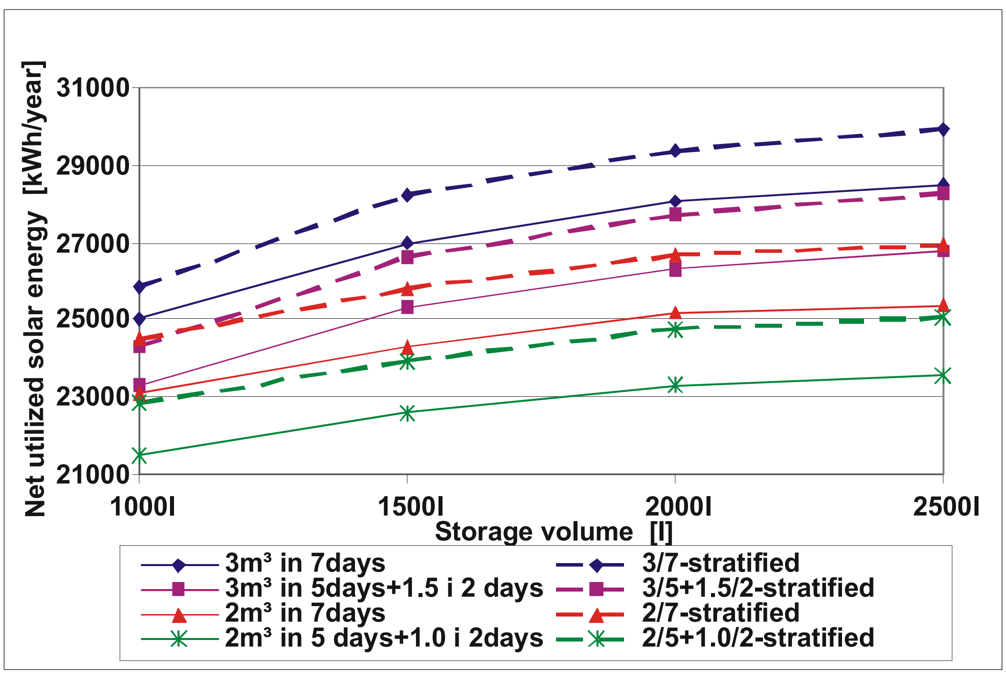

Figure 22: Net utilized solar energy as a function of the storage volume for the system with a 59.7 m^2 Batec-Marstal solar collector.

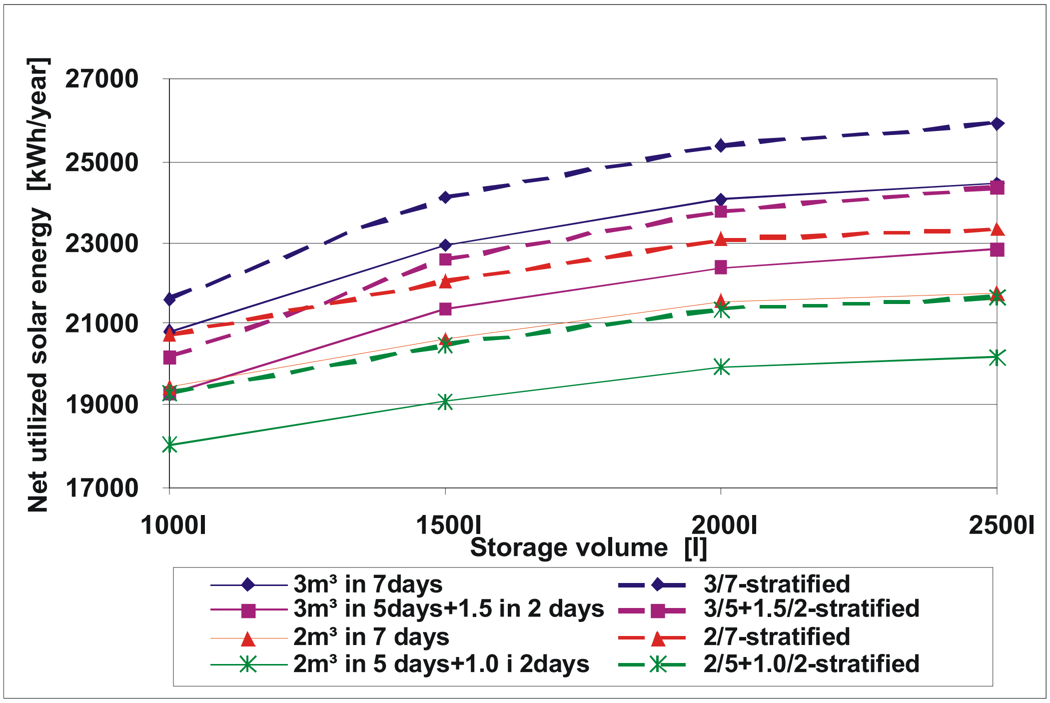

Figure 23: Net utilized solar energy as a function of the storage volume for the system with a 60 m^2 BA 30 solar collector.

3.2.2 Choice of solar collector and solar collector area.

On the basis of the calculations, it is possible to compare the net utilized solar energy of the solar heating system for different solar collectors for each tapping profile. In the figures 24-31 the net utilized solar energy as a function of the storage volume is shown for all the tapping profiles. Figures 24-27 take the system with about 40 m^2 solar collectors as their starting point, and figures 28-31 the system with about 60 m^2. It is evident that the new HT solar collector is much better with regard to performance than the other solar collectors. The Batec-Marstal solar collector is somewhat poorer, and the old HT solar collector is definitely the worst one. Her it should be noted that it is a little difficult to compare the Batec-Marstal solar collector with the other collectors, as the efficiency of the solar collector was determined with water as solar collector fluid.

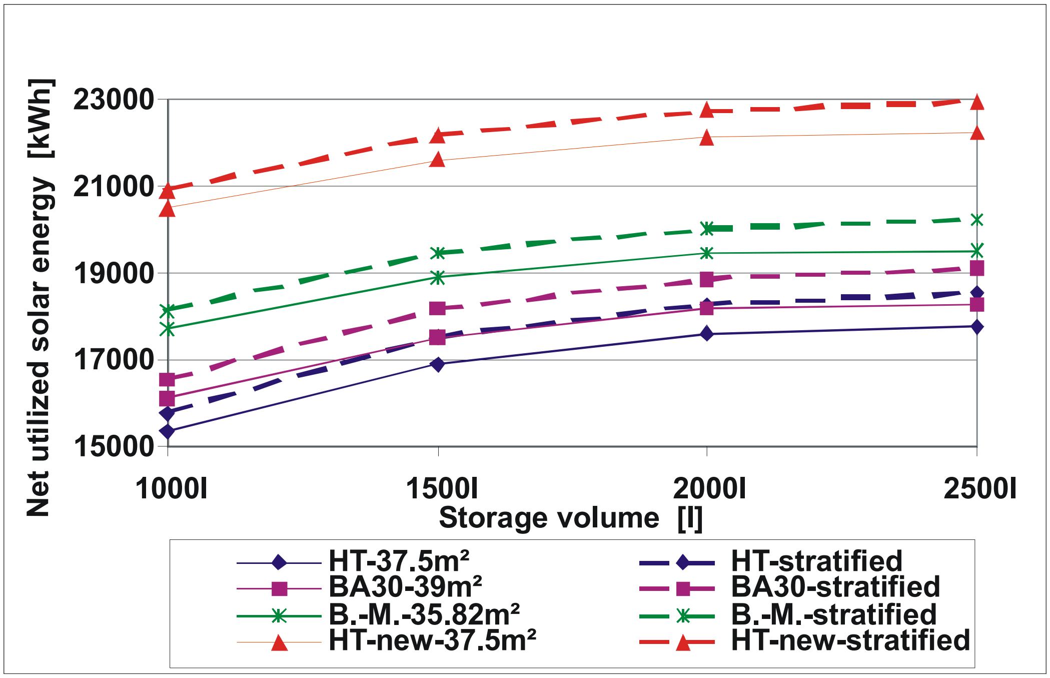

Figure 24: Net utilized solar energy of the solar heating system with about 40 m^2 different solar collectors as a function of the storage volume for the tapping profile of 3 m^3 for 7 days.

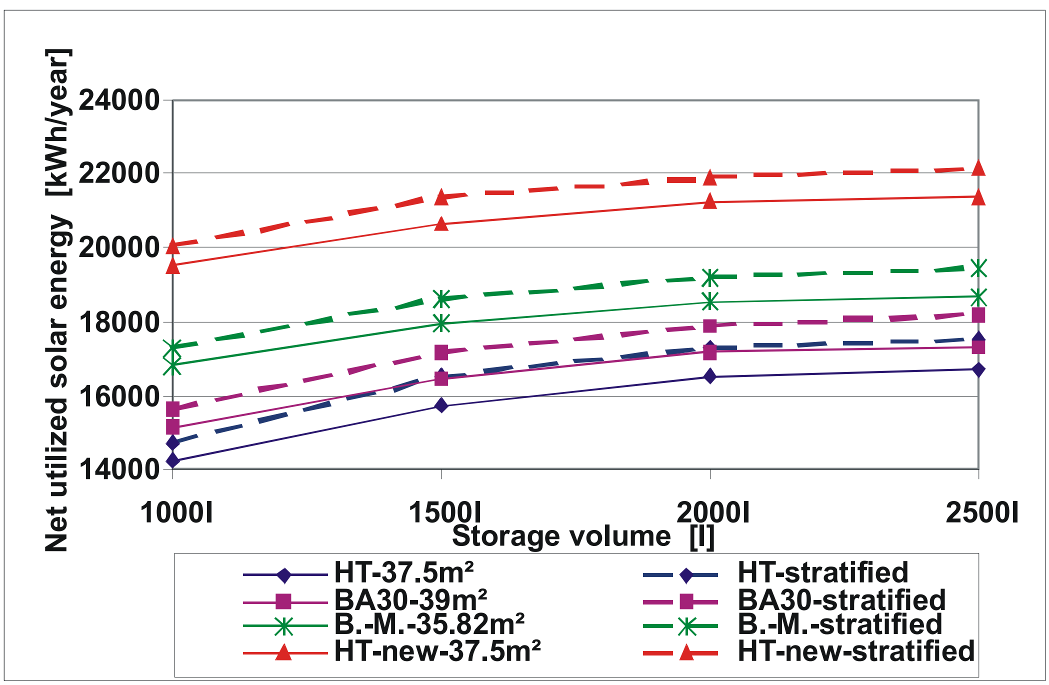

Figure 25: Net utilized solar energy of the solar heating system with about 40 m^2 different solar collectors as a function of the storage volume for a tapping profile of 3 m^3 for 7 days + 1.5 m^3 for 2 days.

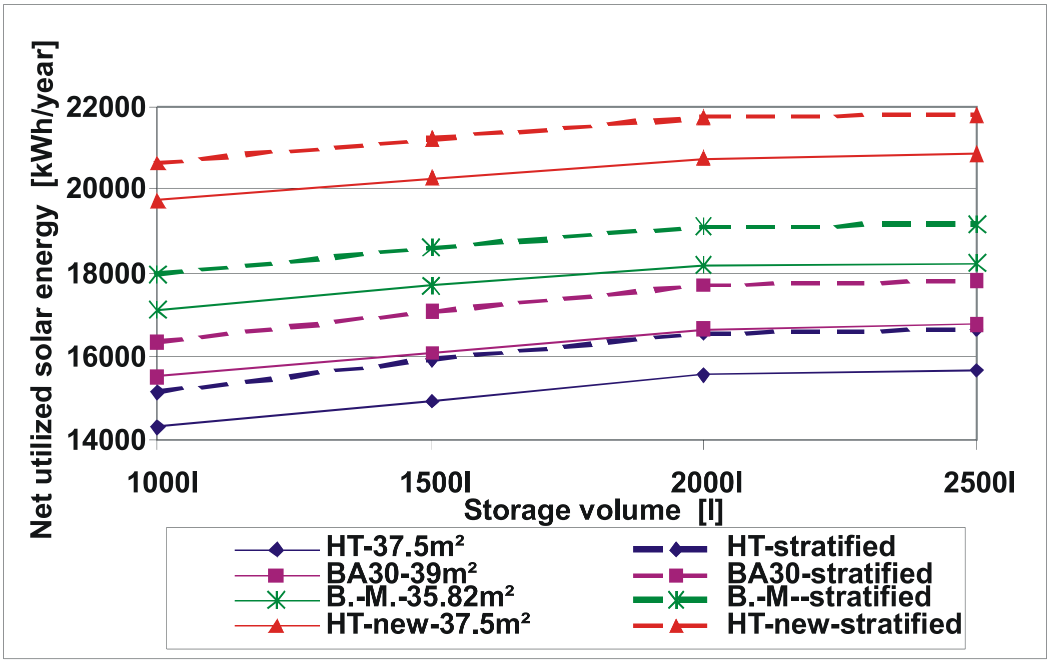

Figure 26: Net utilized solar energy of the solar heating system with about 40 m^2 different solar collectors as a function of the storage volume for a tapping profile of 3 m^3 for 5 days + 1.5 m^3 for 2 days.

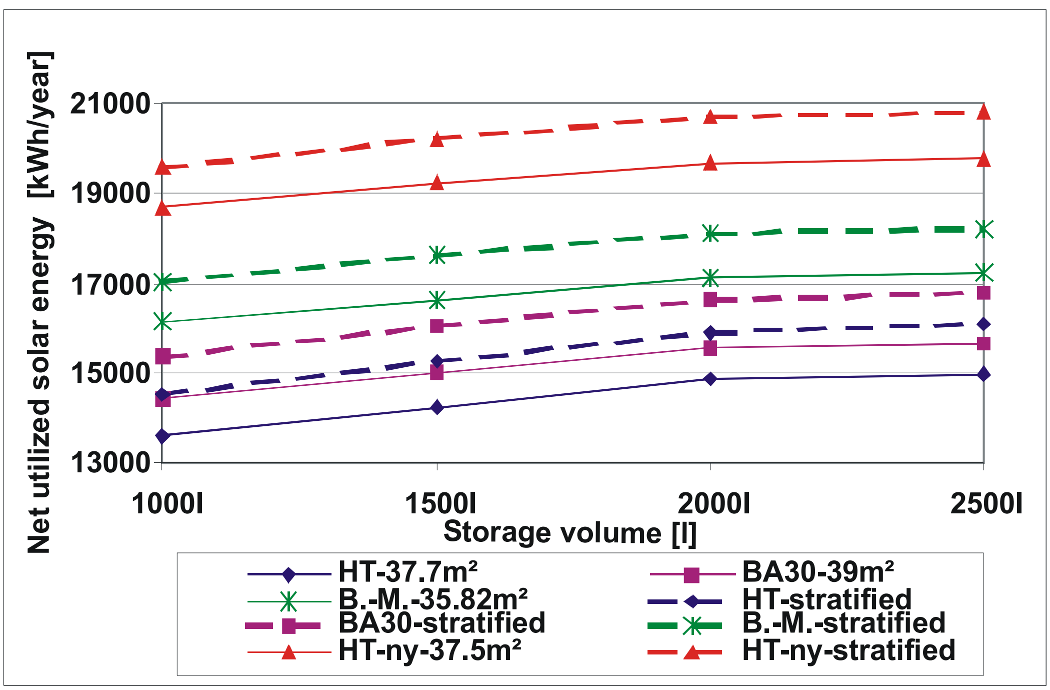

Figure 27: Net utilized solar energy of the solar heating system with about 40 m^2 different solar collectors as a function of the storage volume for a tapping profile of 2 m^3 for 5 days + 1.0 m^3 for 2 days.

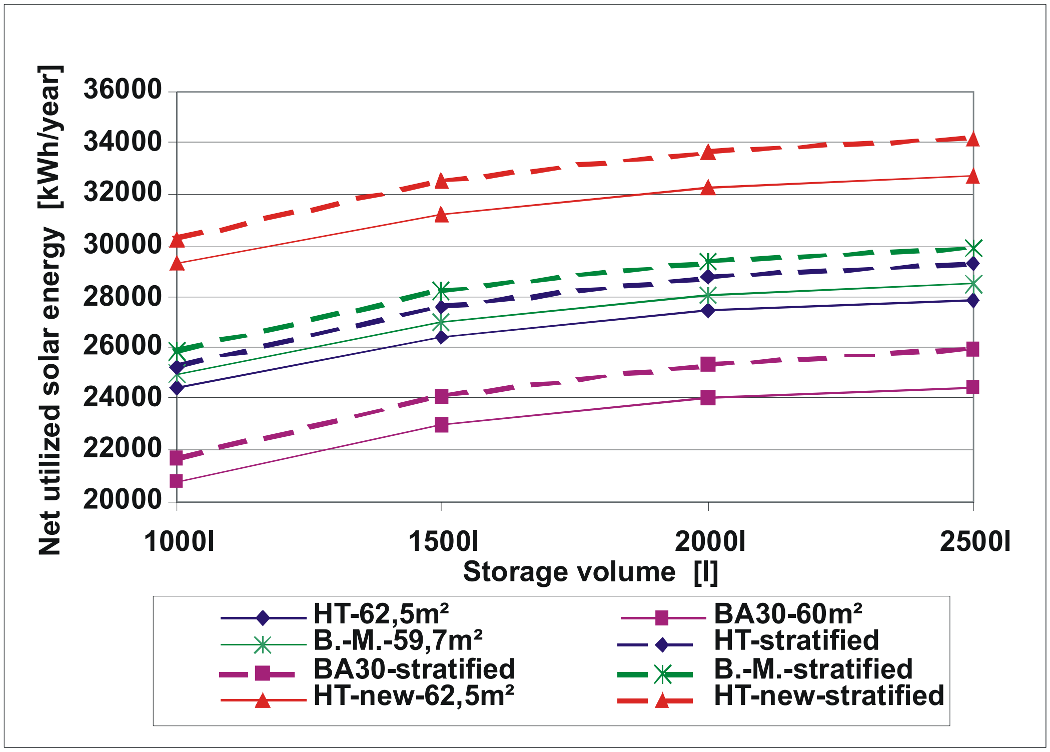

Figure 28: Net utilized solar energy of the solar heating system with about 60 m^2 different solar collectors as a function of the storage volume for a tapping profile of 3 m^3 for 7 days.

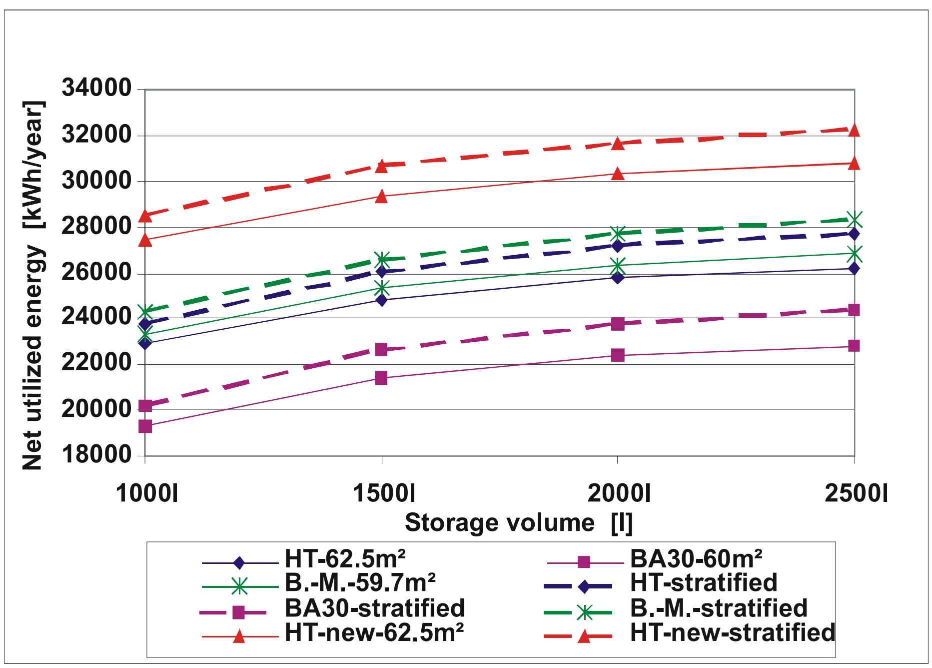

Figure 29: Net utilized solar energy of the solar heating system with about 60 m^2 different solar collectors as a function of the storage volume for a tapping profile of 3 m^3 for 5 days + 1.5 m^3 for 2 days.

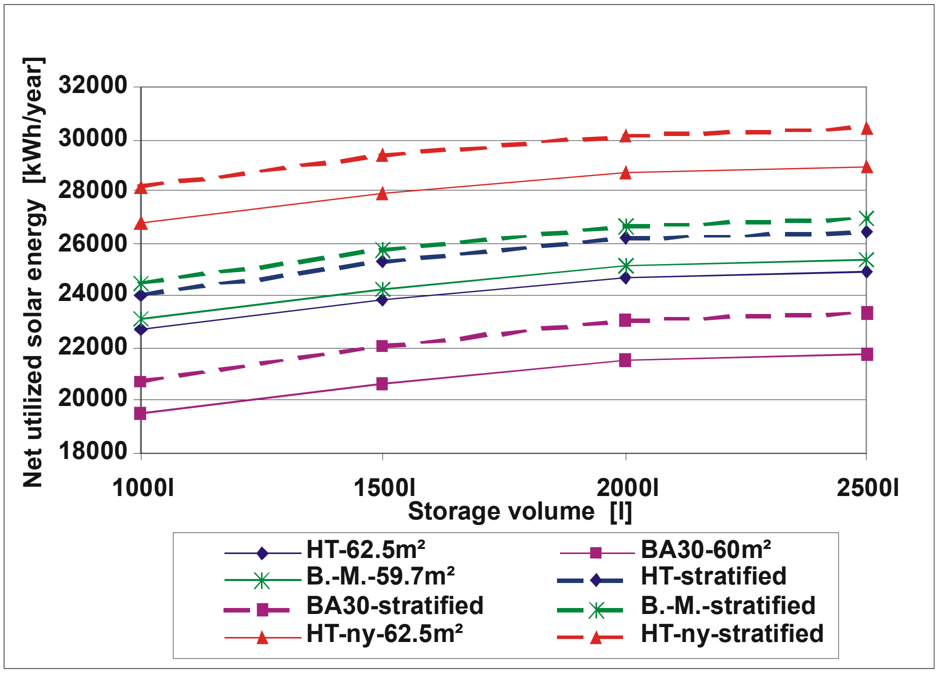

Figure 30: Net utilized solar energy of the solar heating system with about 60 m^2 different solar collectors as a function of the storage volume for a tapping profile of 2 m^3 for 7 days.

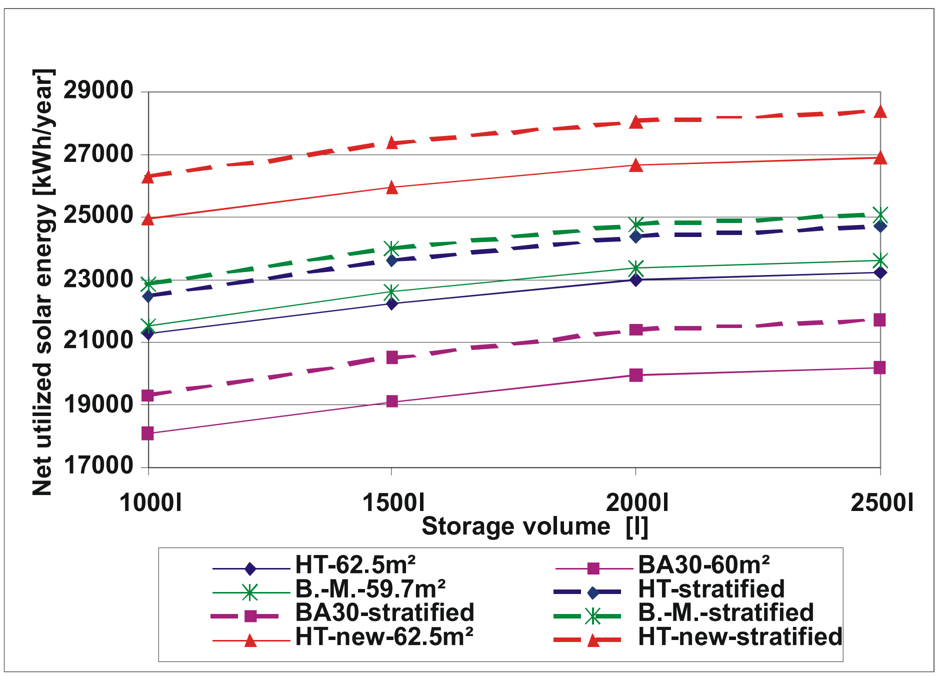

Figure 31: Net utilized solar energy of the solar heating system with about 60 m^2 different solar collectors as a function of the storage volume for a tapping profile of 2 m^3 for 5 days+1.0 m^3 for 2 days.

In figures 32 and 33, the curves for the net utilized solar energy of the solar heating system are drawn as a function of the solar fraction on a yearly basis. The only difference between the models of figure 32 and figure 33 is the inlet from the solar collector loop. The solar fraction is defined as the ratio between the net utilized solar energy and the heat demand, which is the sum of the hot-water consumption and the heat loss of the circulation pipe.

The figures demonstrate that the larger the solar collector area, the higher the solar fraction becomes, whereas the net utilized solar energy of the solar heating system per m^2 solar collector goes down.

Figures 34-37 illustrate how the thermal performance of the solar heating system is affected by the changes in the consumption pattern. The larger the consumption, the higher the thermal performance of the solar heating system becomes. An interesting fact is that at small solar collector areas the old HT solar collector performs somewhat less than BA30, whereas the order is changed at larger solar collector areas. The explanation is probably that at larger solar collector areas the temperature of the mean solar collector fluid will rise, and at higher mean fluid temperatures the HT solar collector is more efficient, see figure 13.

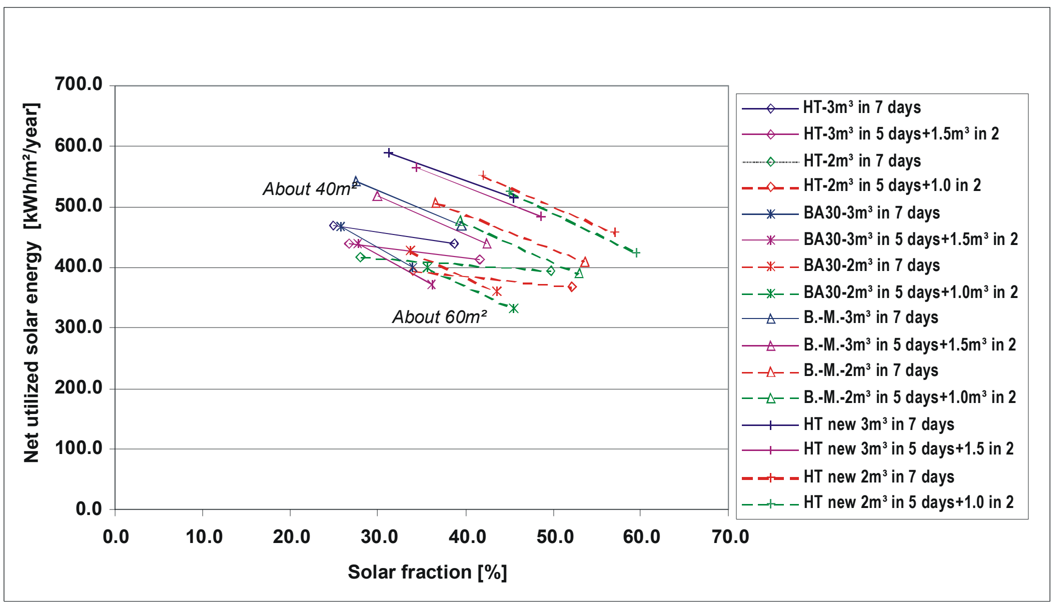

Figure 32: The net utilized solar energy of the solar heating system as a function of the solar fraction for different solar collectors and solar collector areas (2000 l storage with fixed inlet from the solar collector loop).

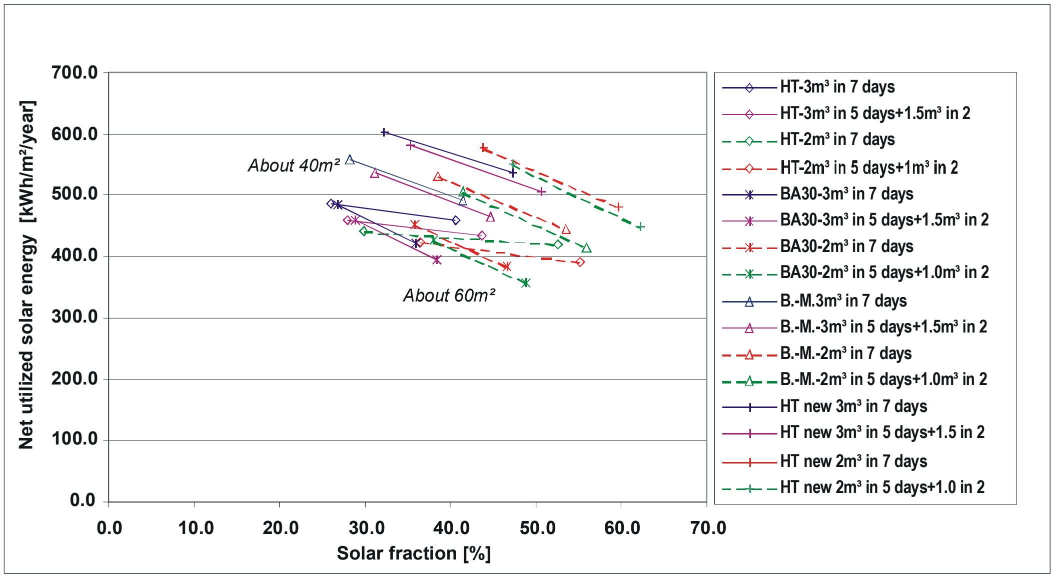

Figure 33: The net utilized solar energy of the solar heating system as a function of the solar fraction for different solar collectors and solar collector areas (2000 l storage with stratified inlet from the solar collector loop).

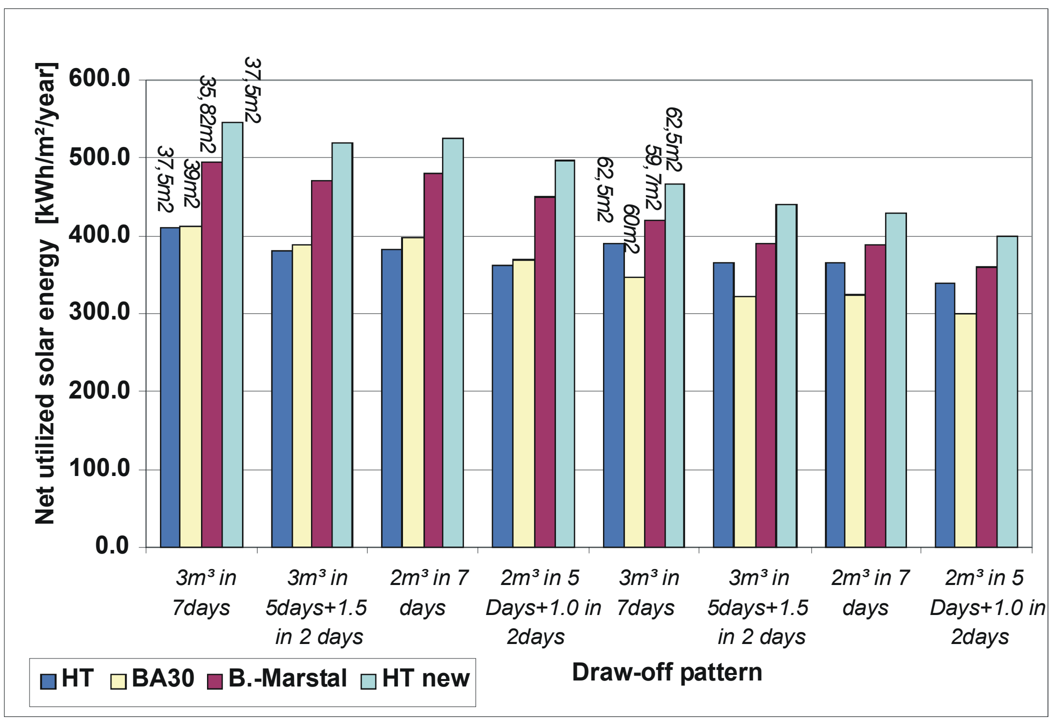

Figure 34: The net utilized solar energy of the solar heating system per m² solar collector as a function of the consumption pattern for different solar collectors with 1000 l storage.

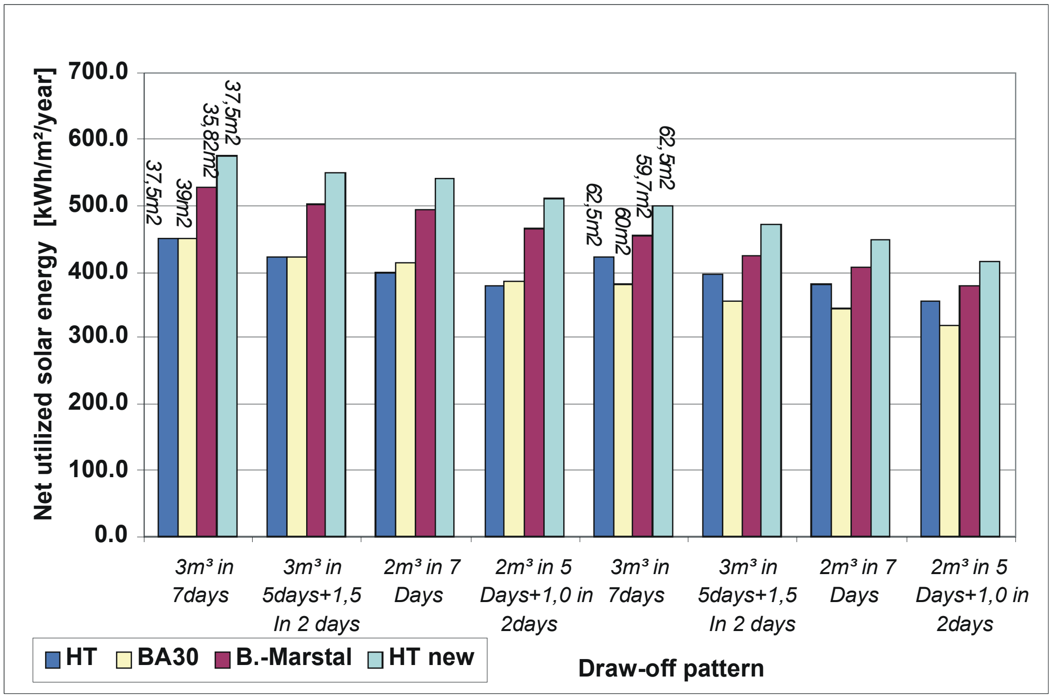

Figure 35: The net utilized solar energy of the solar heating system per m² solar collector as a function of the consumption pattern for different solar collectors with 1500 l storage.

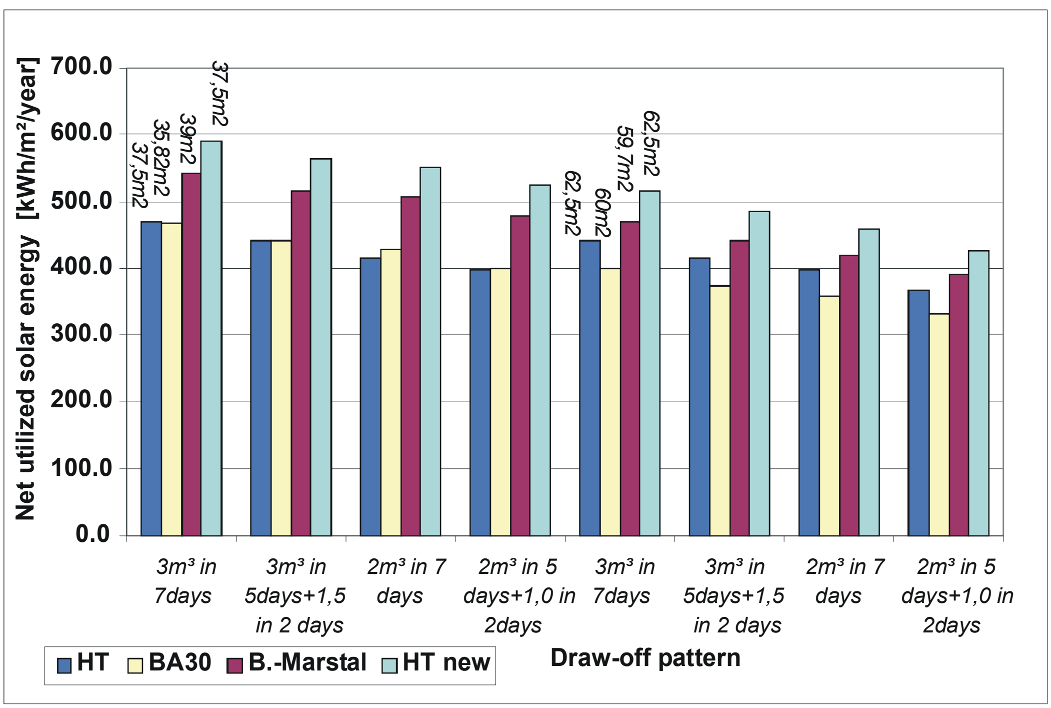

Figure 36: The net utilized solar energy of the solar heating system per m² solar collector as a function of the consumption pattern for different solar collectors with 2000 l storage.

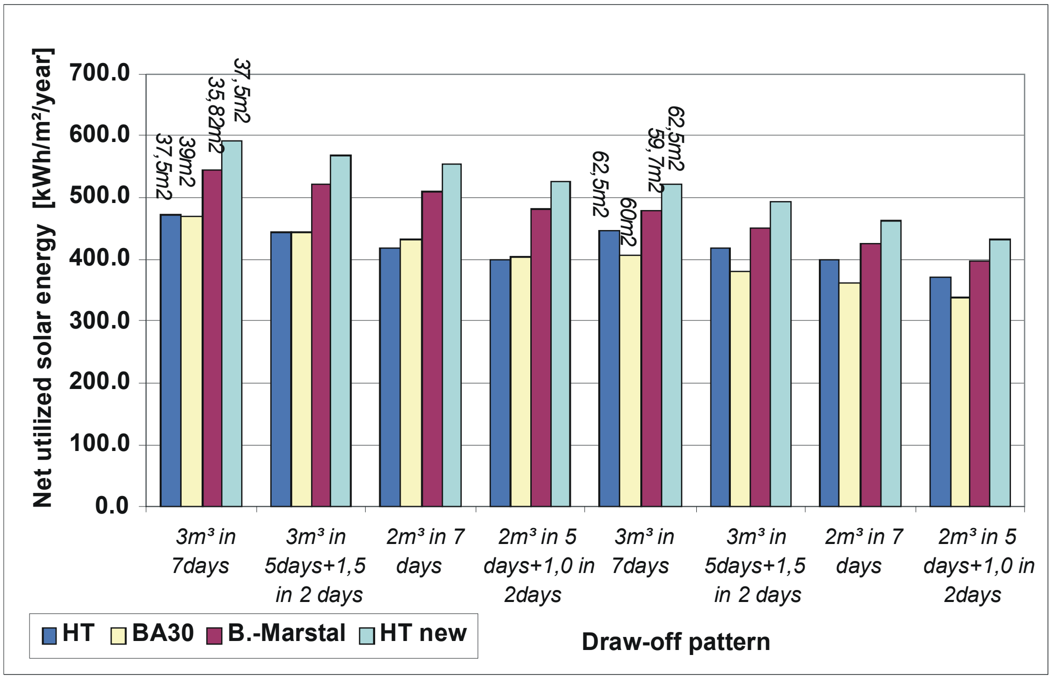

Figure 37: The net utilized solar energy of the solar heating system per m² solar collector as a function of the consumption pattern for different solar collectors with 2500 l storage.

When using the new HT solar collector it is possible to increase the thermal performance of the solar heating system considerably. From figures 38 and 39 it appears that for the solar heating system of the school, the yearly thermal performance of the system will increase from 15 to 38% by replacing the old HT solar collectors with the new collectors.

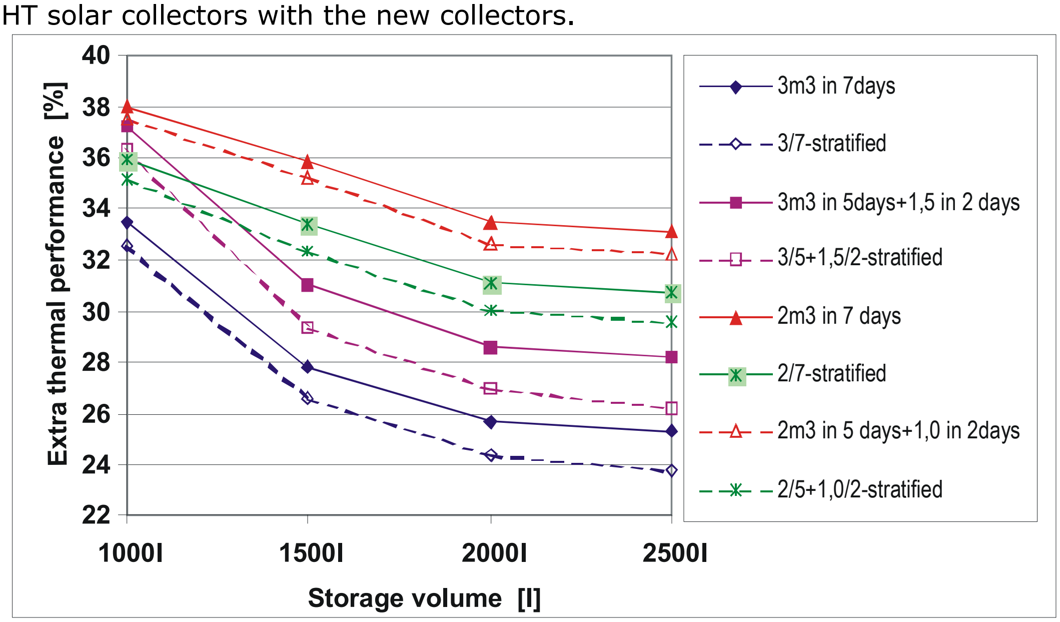

Figure 38: Increase of the performance of the solar heating system (with about 40 m² solar collectors) by using the new HT solar collector instead of the old HT solar collector.

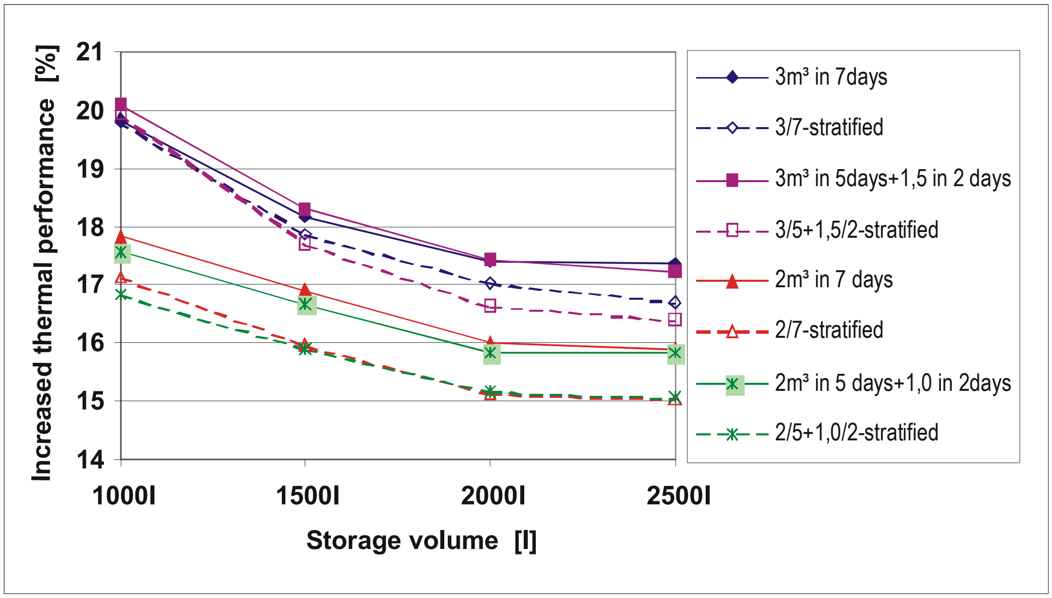

Figure 39: Increase of the thermal performance of the solar heating system (with about 60 m^2 solar collectors) by using the new HT solar collector instead of the old HT solar collector.

3.2.3 The circulation loop

To clarify how heat loss from the circulation pipe affects the thermal performance of the solar heating system, calculations were made for a solar heating system where the running period of the circulation pump varies. A solar heating system with a heat storage of 2000 litres, with HT solar collector, and with fixed inlet position from the solar collector loop is taken as a starting point. Calculations are made on a system with the circulation pump in operation for either 6 or 12 hours a day.

Figure 40 shows that the heat loss from the circulation pipes is of no particular importance for the performance of the solar heating system. Figure 41 shows how much the heat loss from the circulation pipe matters to the energy supply from the auxiliary energy supply system. It is no surprise that the smaller the heat loss, the smaller energy is required. By restricting the operation time of the circulation pump from 12 to 6 hours per day it is possible to save about 3500-4000 kWh per year, but on the other hand it is a question of the consumers' comfort.

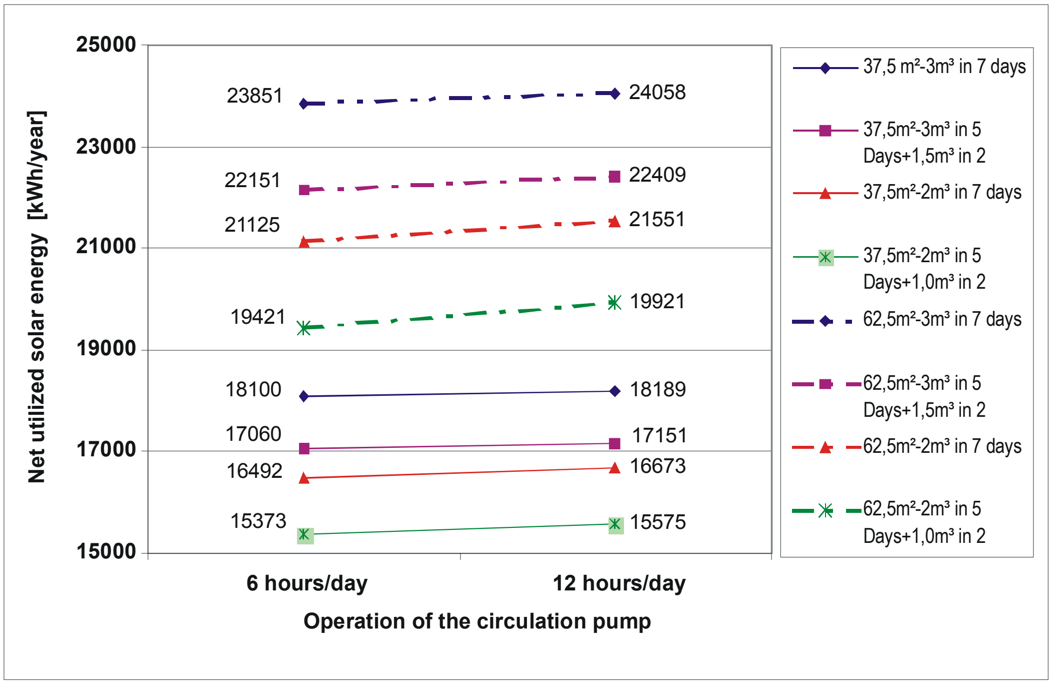

Figure 40: The net utilized solar energy of the solar heating system as a function of the operating hours of the circulation pump.

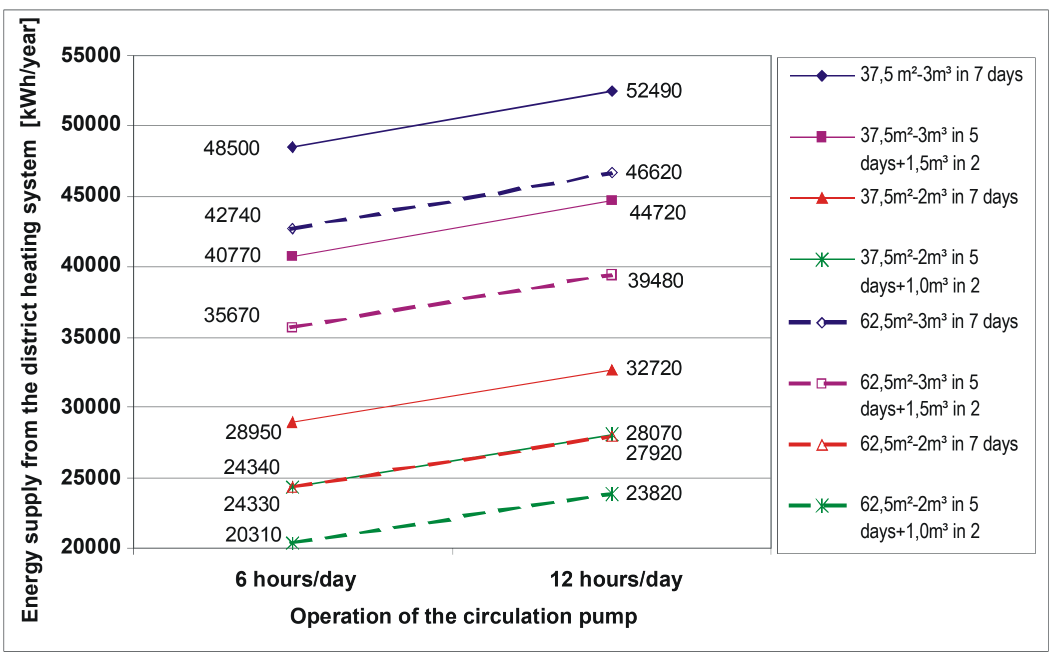

Figure 41: Energy supply from the district heating system as a function of the operating hours of the circulation pump.

3.3 Data for the kindergarten

3.3.1 Solar collector type

The solar collector type is defined by means of component Type 1. For the kindergarten as well as for the school, calculations are made with the same 4 different solar collectors, i.e. data for solar collectors are the same as for the school. For the kindergarten, however, calculations are made for a solar heating system with 20 m^2 and 40 m^2 solar collectors. I.e., the tables 1-4 can be taken as a starting point for the school with the exception of the parameters 2 and 3.

All the solar collectors are facing south with a tilt angle of 45°. Data input for the parameters 2 and 3 for different solar collectors appear from tables 12-15.

Paramete r	Specifications	Unit	Value
2	Number of solar collectors	-	2/3
3	Total transparent area	m^2	23.06/37.5

Table 12: Parameters for HT solar collector.

Parameter	Specifications	Unit	Value
2	Number of solar collectors	-	7/13
3	Total transparent area	m^2	21/39

Table 13: Parameters for BA30 solar collector.

Parameter	Specifications	Unit	Value
2	Number of solar collectors	-	3/5
3	Total transparent area	m^2	23.88/35.82

Table 14: Parameters for Batec-Marstal solar collector.

Parameter	Specifications	Unit	Value
2	Number of solar collectors	-	3/5
3	Total transparent area	m^2	25.06/37.5

Table 15: Parameter for the new HT solar collector.

3.3.2 The tank

The same tank as for the school is taken as a starting point, i.e., the tank is made of ordinary steel and insulated with 100 mm mineral wool which has a thermal conductivity of 0.045 W/(m·K). If there is not room enough in the basement, the tank can be placed in the laundry, which is just above the basement. There is room enough for a 2 m high tank. Data input for the tank appears from table 18.

For the kindergarten calculations are made for 3 different storage volumes: 1000, 1500 and 2000 litres.

Just as for the solar heating system of the school, the upper part of the storage in the solar heating system of the kindergarten is heated via the external heat exchanger of the district heating system in order to keep the temperature at the top of the storage at 55°C. The volume, which is heated by the auxiliary energy supply system, must on the one hand be as small as possible, but on the other hand there must be enough hot water to meet the consumption. The necessary auxiliary volume is found by means of parameter variations in TRNSYS (parameter 30 ”fvout” in table 18), and that volume is naturally different from one tapping profile to another:

For the tapping profiles 2 m^3 for 7 days and 3 m^3 for 7 days, the auxiliary volume must be about 200 l (at a volume flow rate of the domestic water through the external heat exchanger of the district heating system of 1100 and 1200 l/h, respectively).

For the tapping profiles 4 m^3, 5 m^3 and 6 m^3 for 7 days, the auxiliary volume must be about 400 l (at a volume flow rate of the domestic water through the external heat exchanger of the district heating system of 1200, 1300 and 1500 l/h, respectively).
The outlet position to the district heating loop for different tapping profiles, expressed as the relative height of the tank, appears from table 16 (0 – the bottom and 1- the top). The tank is always 2 m high.

The parameter 33 (”sens4” in table 18) states the place of the temperature sensor for control of the district heating system. Its position is somewhat higher than the outlet to the district heating loop.

Tapping profiles / Tank size	2 m^3 for 7 days and 3 m^3 for 7 days **(200 l)**	4 m^3 for 7 days, 5 m^3 for 7 days, 6 m^3 for 7 days **(400 l)**
2000 l	0.9	0.8
1500 l	0.87	0.73
1000 l	0.8	0.6

Table 16: The outlet to the district heating loop (stated as relative height of the tank).

Solar heat is transferred to the lower part of the tank where the temperature of the water is lower, so that is possible to transfer heat from solar collectors at low temperatures. At parameter variations in TRNSYS (parameter 20 ”sfind” in table 18) the level is found at which the fixed inlet from the solar collector loop is best connected, so that the thermal performance becomes as large as possible. It is important to lead the solar heat into the tank at a right temperature level, so that the thermal stratification is not spoiled. It is clear that the best fixed inlet position from the solar collector loop (and with this the thermal performance of the solar heating system) depends very much on the solar collector area, and in addition to that also the tapping profile and the tank size will play a part. The best inlet position from the solar collector loop for different tapping profiles, solar collector areas, and tank sizes appears from table 17, where the best inlet position is stated as the relative height of the tank (0 – the bottom and 1- the top).

Tapping profiles / Tank size	2 m^3 for 5 days and 3 m^3 for 5 days		4 m^3 for 7 days, 5 m^3 for 7 days, 6 m^3 for 7 days	
Solar collector area	20 m^2	40 m^2	20 m^2	40 m^2
2000 l	0.7	0.7	0.6	0.6
1500 l	0.6	0.6	0.5	0.5
1000 l	0.6	0.6	0.5	0.5

Table 17: The best inlet position from the solar collector loop (stated as relative height of the tank).

Parameter	Specifications	Unit	Value
1	The height of the tank	m	2
2	The volume of the tank	m^3	1.0/1.5/2.0
3	The thermal capacity of the fluid	kJ/kg-K	4.18
4	The density of the fluid	kg/m^3	1000
7	Heat loss from the bottom	C	10
8	Heat loss from the top	W/K	
9	Heat loss from the sides	W/K	
11		W/K	
17	Relative height of the inlet for cold domestic water supply	-	0
18	Relative height of the outlet for tapping of hot domestic water	-	1
20	Relative height of the inlet from the solar collector loop	-	**sfind**
21	Relative height of the outlet to the solar collector loop	-	0

22	Stratified inlet from the solar collector loop? (yes=1)	-	0/1
23	Relative height of the inlet fro the circulation pipe loop	-	**ckind**
24	Relative height of the outlet to the circulation pipe loop	-	1
25	Stratified inlet from the circulation pipe loop? (yes=1)	-	0
29	Relative height of the inlet from the district heating system loop	-	0.99
30	Relative height of the outlet to the district heating system loop	-	**fvout**
31	Stratified inlet from the district heating system loop (yes=1)	-	0
32	Relative position of the 1st temperature sensor (bottom)	m	0
33	Relative position of the 4th temperature sensor	m	**sens4**
79	Number of temperature layers in the tank	-	300

Table 18: Parameters for the tank.

3.3.3 Control of the solar heating system

For the kindergarten the same control principle is used as for the school, see section 3.1.3.

3.3.4 Heat exchanger

As the solar heating systems for the school and the kindergarten are identical, also a counter flow plate heat exchanger in the district heating system loop and in the solar collector loop for the solar heating system in the kindergarten are used. The procedure of calculating the two heat exchangers for the kindergarten is the same as for the school, see section 3.1.4.

3.4 The performance of the solar heating system for the kindergarten

3.4.1 Choice of the storage volume

Calculations were carried out for different solar collectors with 3 storage volumes: 1000 l, 1500 l and 2000 l with fixed as well as stratified inlet from the solar collector loop.

As the measured consumption of the kindergarten lies between 3 and 6 m^3 per day, to begin with 4 different tapping profiles are allowed for: 3, 4, 5 and 6 m^3 on weekdays and no consumption at weekends to elucidate how the consumption pattern affects the performance of the solar heating system. In this case the calculations are carried out with about 40 m^2, and about 60 m^2 with the old HT solar collector, Batec-Marstal and BA30. The results of these calculations in the form of graphs appear from figures 42-47.

As it turned out that there is no room for such a large system, and as the future consumption of the domestic water is expected to decrease because of increased use of dishwashers, the calculations are also carried out with the consumer profiles of 2, 3 and 4 m^3 on weekdays. In this case the calculations are carried out with a solar collector field of about 20 and 40 m^2, and in these simulations the old HT solar collector is replaced by the new one. The results of these calculations in the form of graphs appear from figures 48-53.

Figures 42-53 show the net utilized solar energy of the solar heating system with different solar collectors as a function of the storage volume. For each tapping profile the auxiliary volume, heated by the district heating system, is kept constant, whereas the best inlet position from the solar collector loop for different storage volumes is found by means of the simulations.
The net utilized solar energy is shown both for the best placed fixed inlet from the solar collector loop and for an inlet where stratification pipes are used, so that the domestic water is transferred to the heat storage at the ”right” level.
The net utilized solar energy is defined as the size of the hot-water consumption plus the heat loss of the circulation pipe minus the heat that is transferred to the system from the district heating system.

From figures 42-53 it appears that the larger the storage volume, the greater the thermal performance of the solar heating system becomes. Further can be seen that the larger the consumption, the greater the thermal performance of the solar heating system becomes, yet with the exception of the system with about 20 m^2 solar collectors, see figures 48, 50 and 52 where the curve for the consumer profile of 4 m^3 suddenly lies above, or in some cases somewhat under, the curve for the consumer profile of 3 m^3. The reason for this deviance is that the volume heated by the auxiliary energy supply system is larger for the larger consumption, and therefore the volume heated by solar heat becomes smaller. It is clear that the solar heating system with more solar collectors will perform more.

The storage volume for the solar heating system for the kindergarten with either about 20 m^2, 40 m^2 or 60 m^2 solar collectors should not be smaller than 2000 l.

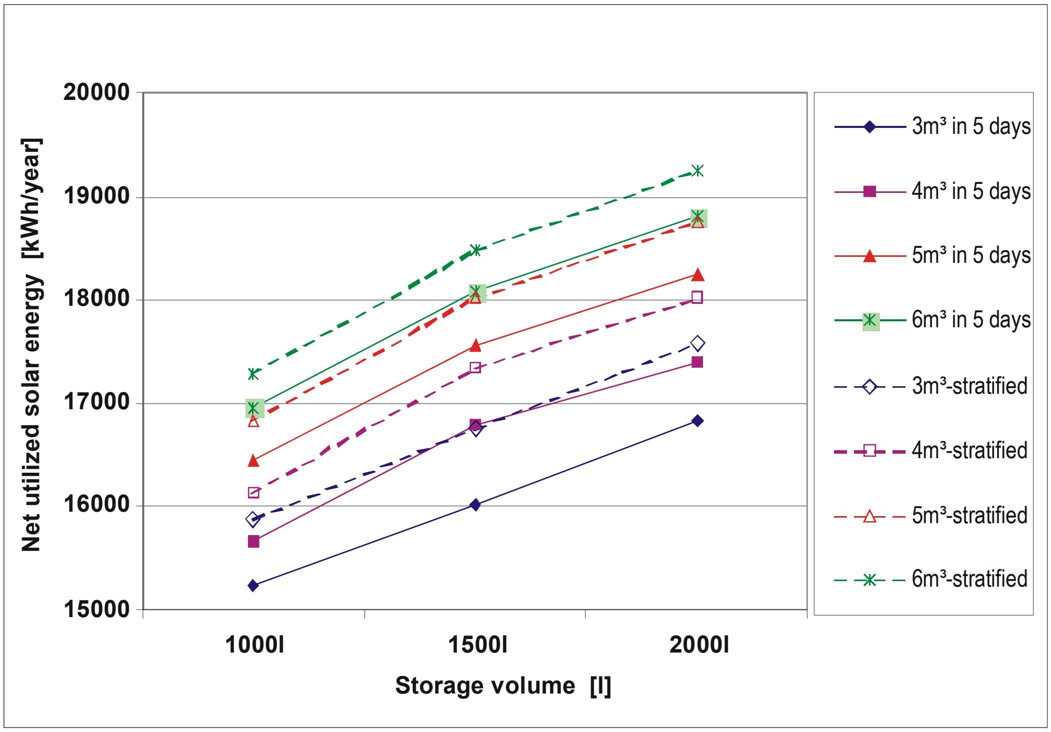

Figure 42: Net utilized solar energy as a function of the storage volume for the system with 37.5 m^2 HT solar collectors.

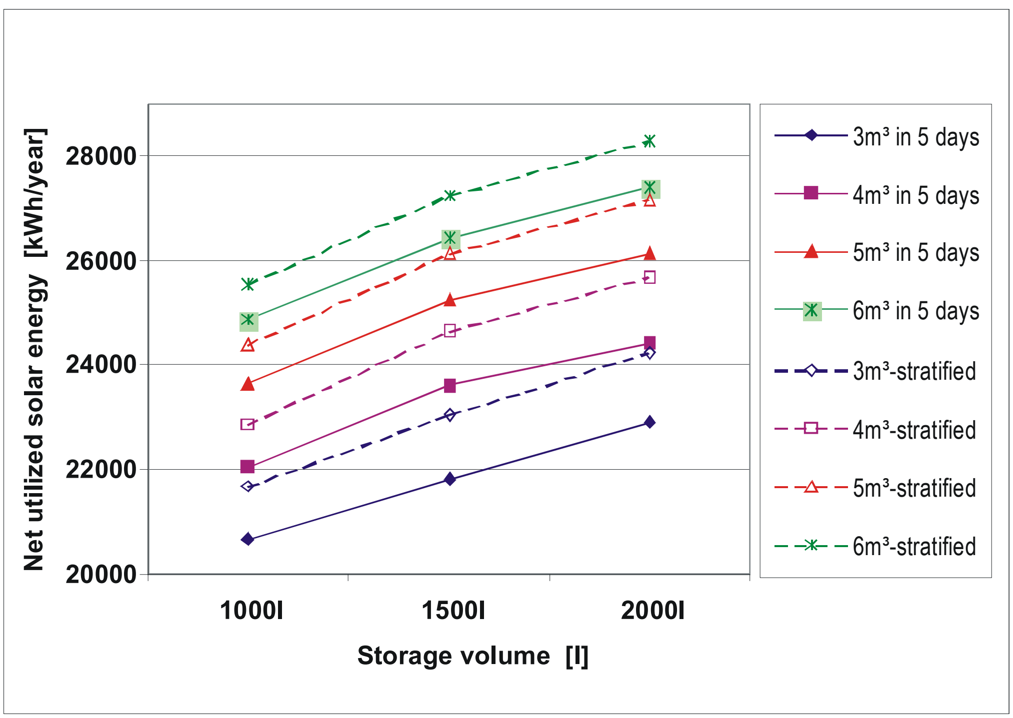

Figure 43: Net utilized solar energy as a function of the storage volume for the system with 62.5 m^2 HT solar collectors.

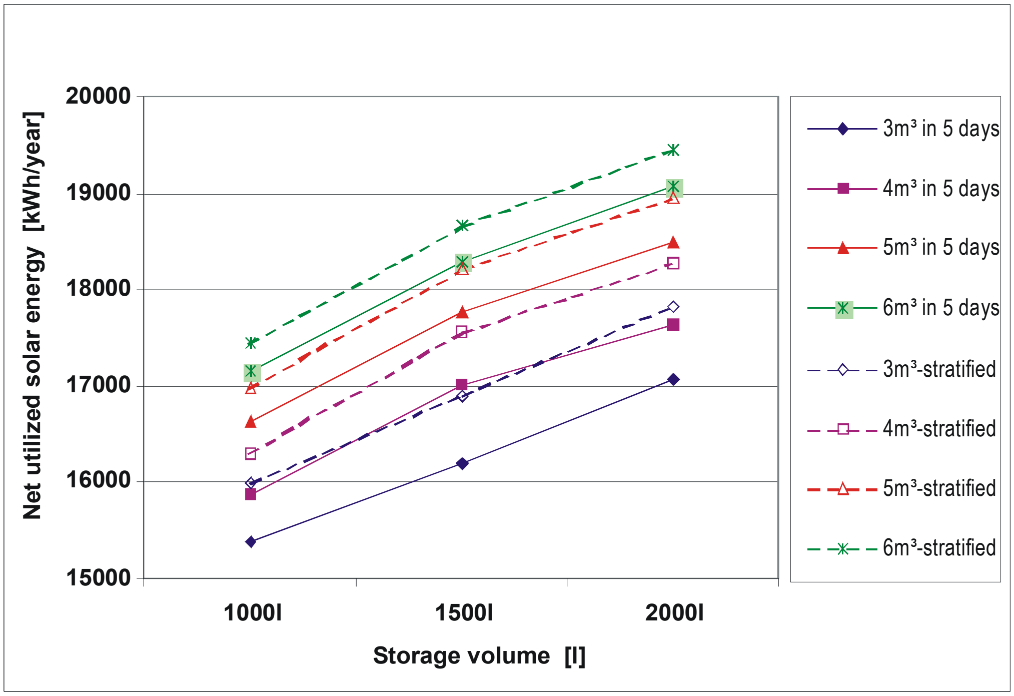

Figure 44: Net utilized solar energy as a function of the storage volume for the system with 35.82 m^2 B.-Marstal solar collectors.

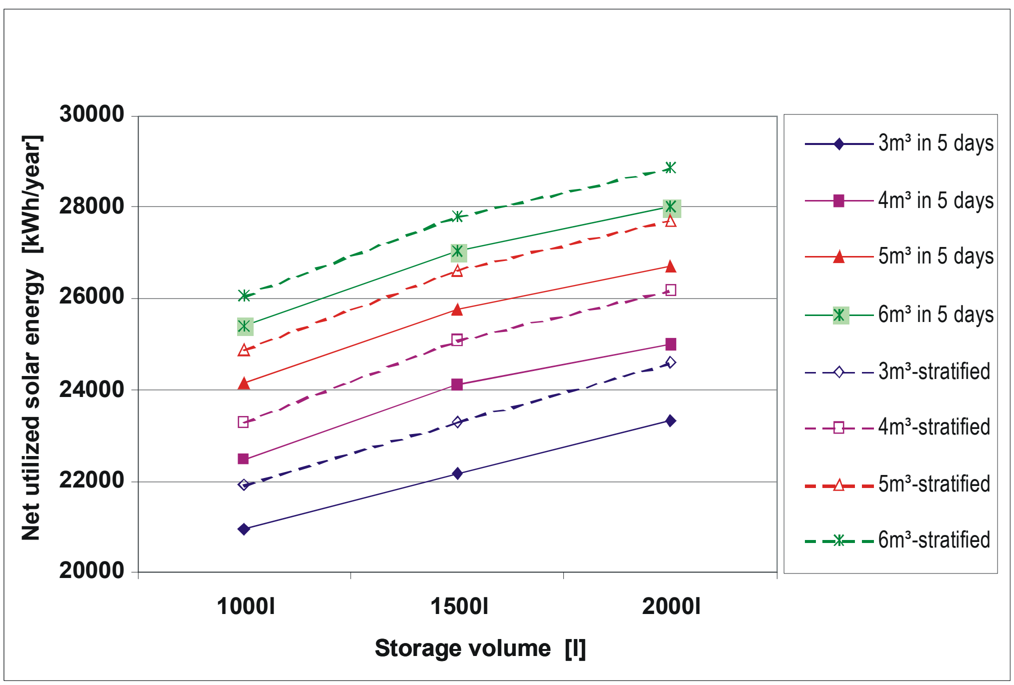

Figure 45: Net utilized solar energy as a function of the storage volume for the system with 59.7 m^2 B.-Marstal solar collectors.

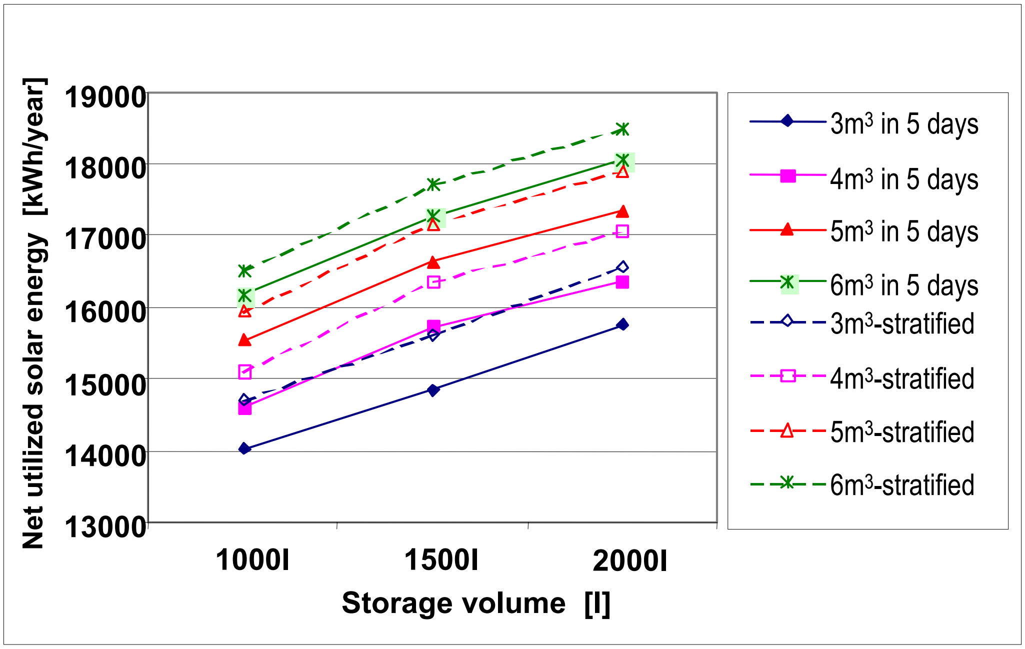

Figure 46: Net utilized solar energy as a function of the storage volume for the system with 39 m^2 BA30 solar collectors.

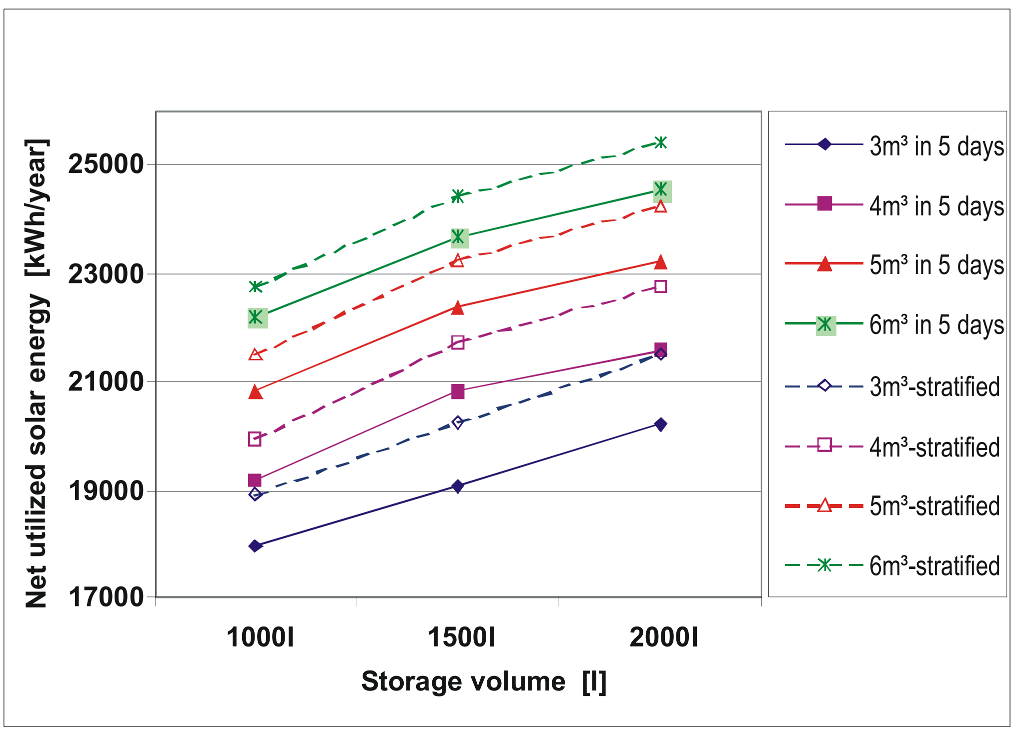

Figure 47: Net utilized solar energy as a function of the storage volume for the system with 60 m^2 BA30 solar collectors.

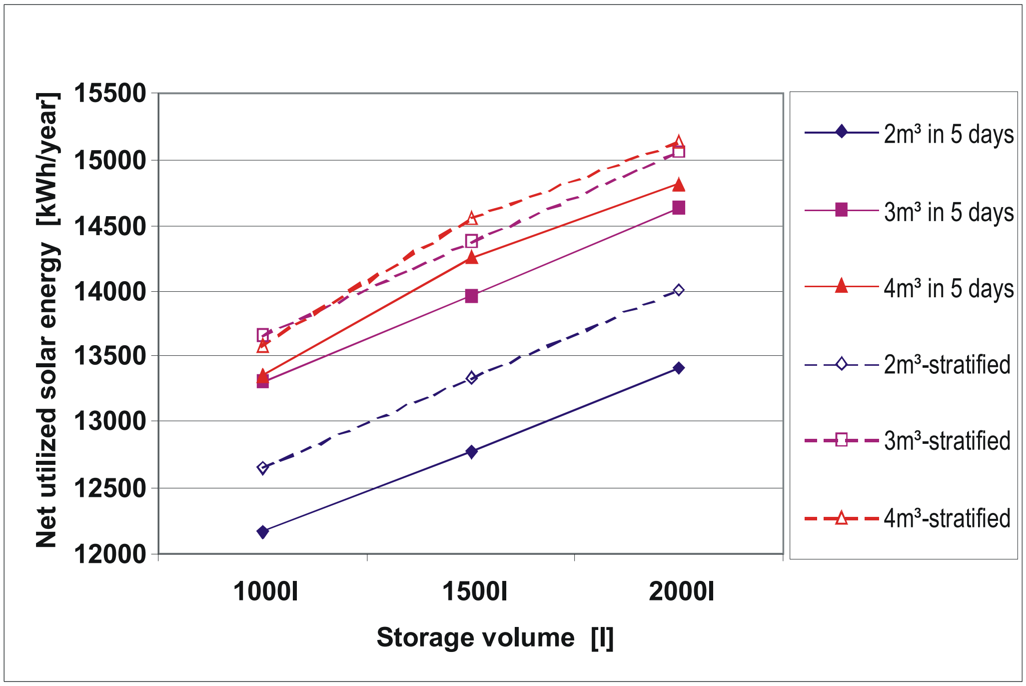

Figure 48: Net utilized solar energy as a function of the storage volume for the system with 25 m^2 new HT solar collectors.

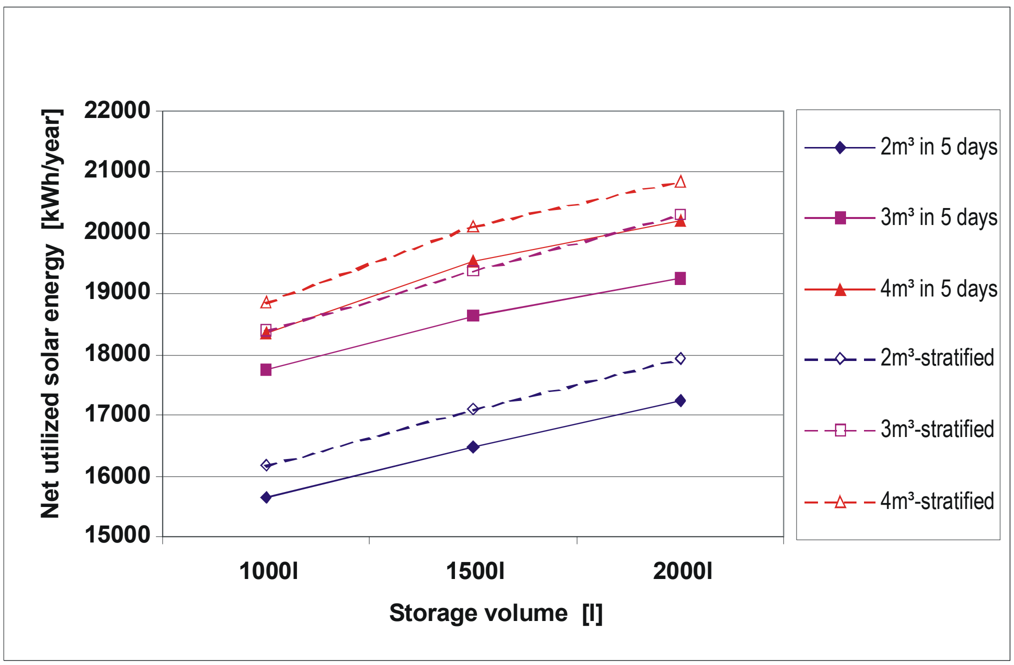

Figure 49: Net utilized solar energy as a function of the storage volume for the system with 37.5 m^2 new HT solar collectors.

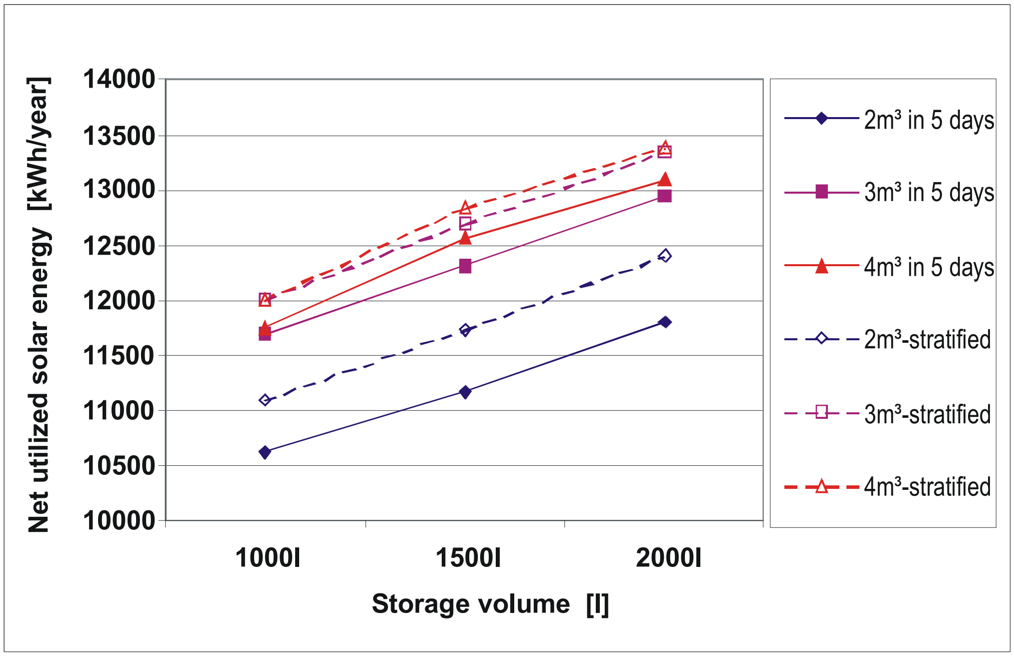

Figure 50: Net utilized solar energy as a function of the storage volume for the system with 23.88 m^2 B.-Marstal solar collectors.

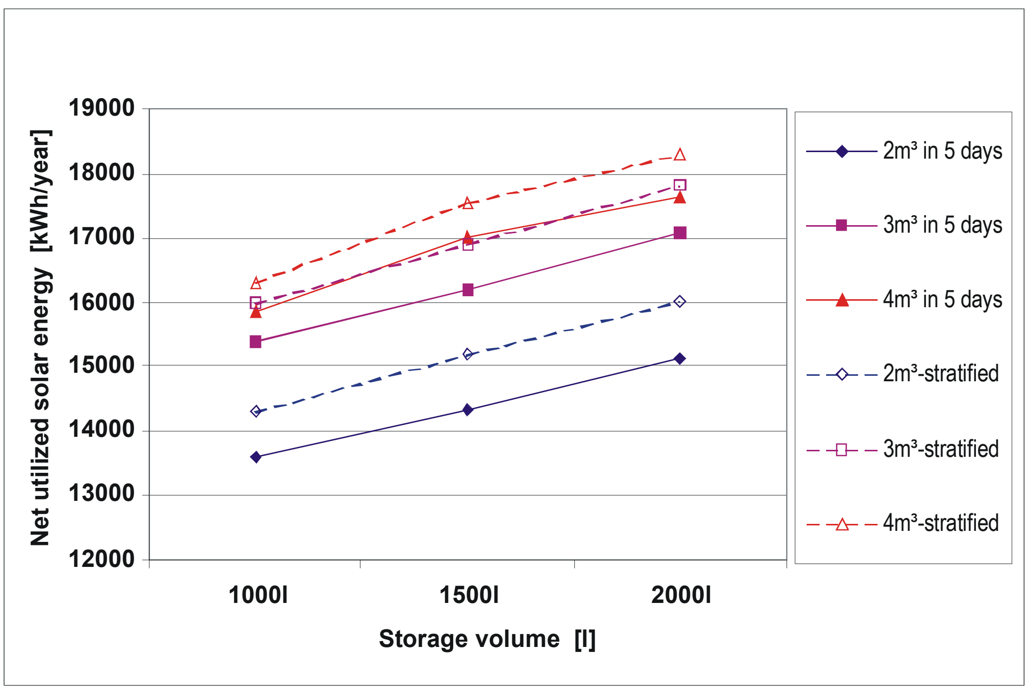

Figure 51: Net utilized solar energy as a function of the storage volume for the system with 35.82 m^2 B.-Marstal solar collectors.

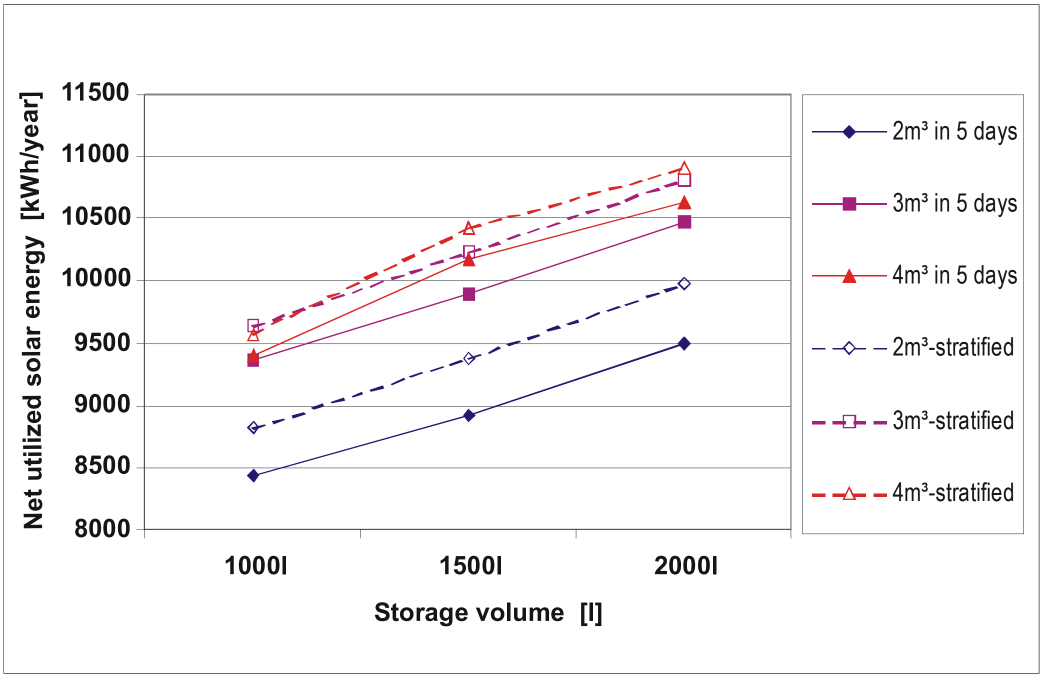

Figure 52: Net utilized solar energy as a function of the storage volume for the system with 21 m^2 BA30 solar collectors.

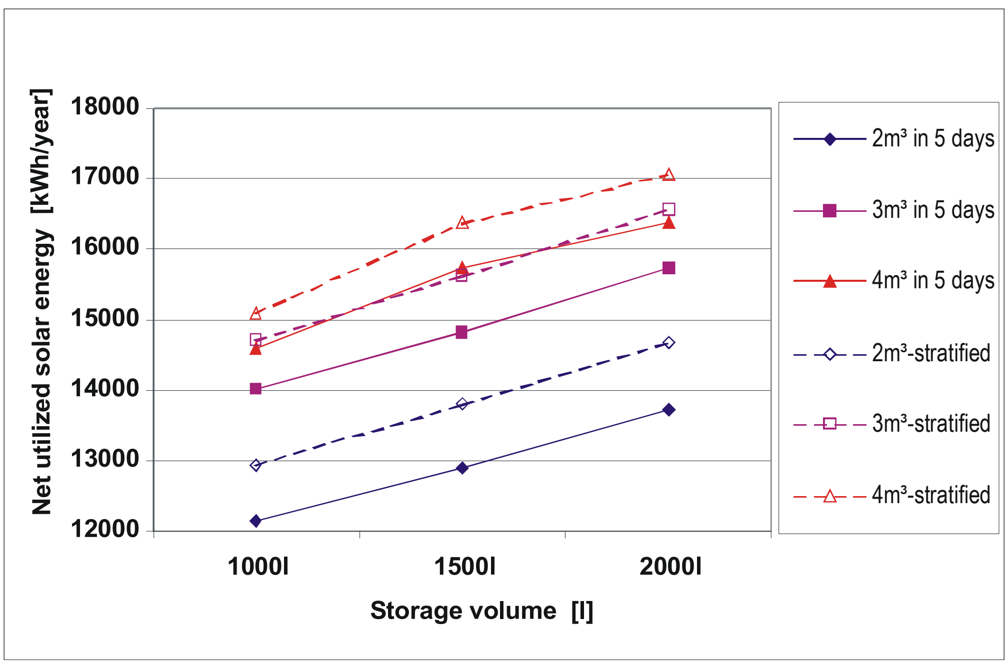

Figure 53: Net utilized solar energy as a function of the storage volume for the system with 39 m^2 BA30 solar collectors.

3.4.2 Choice of solar collector and solar collector area.

As mentioned above, simulations are also carried out for the kindergarten with a solar collector field of about 20 m^2 and 40 m^2 and with tapping profiles of 2, 3 and 4 m^3 per day for 5 days.

On the basis of the calculations it is possible to compare the net utilized solar energy of the solar heating systems for different solar collectors for each tapping profile. In figures 54-59, the net utilized solar energy as a function of the storage volume are shown for all the tapping profiles. The figures 54-56 take the system with about 20 m^2 solar collectors as their starting point and figures 57-59 the system with about 40 m^2. The net utilized solar energy is shown both for the best placed fixed inlet from the solar collector loop and for an inlet with the stratification pipes.

It is clear that the new HT solar collector has a much better performance than the others. Somewhat lower lies the Batec-Marstal solar collector, and BA 30 is the poorest of the three solar collectors. Again, it should be noted here that it is somewhat different to compare the Batec-Marstal solar collector with the others, as the solar collector was tested with water as solar collector fluid.

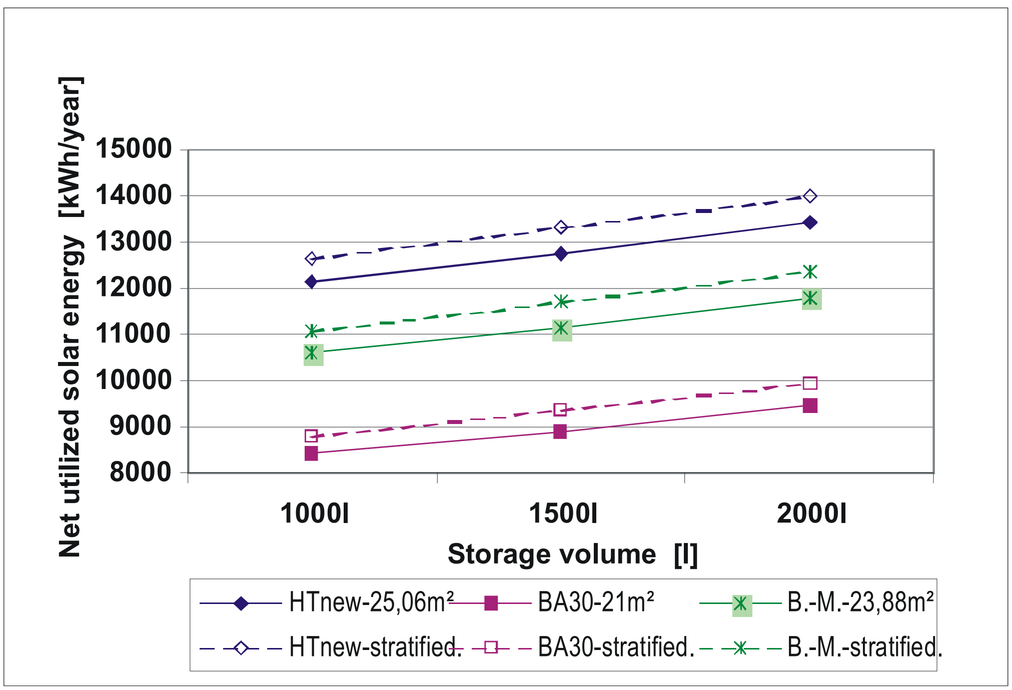

Figure 54: Net utilized solar energy for the solar heating system with about 20 m^2 different solar collectors as a function of the storage volume for a tapping profile of 2 m^3 for 5 days.

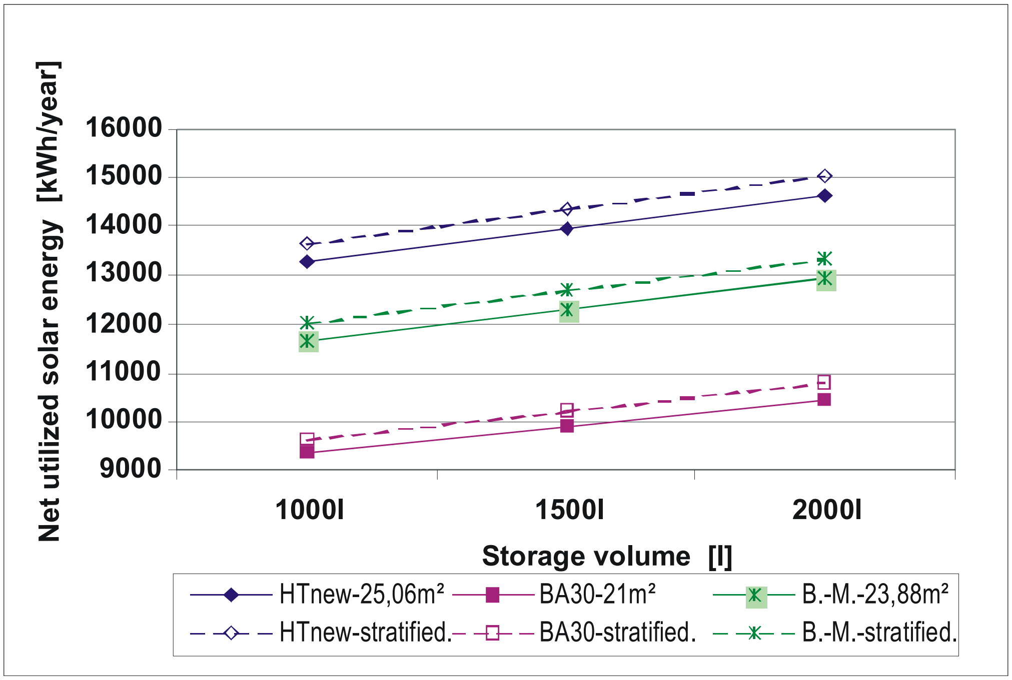

Figure 55: Net utilized solar energy of the solar heating system with about 20 m^2 different solar collectors as a function of the storage volume for a tapping profile of 3 m^3 for 5 days.

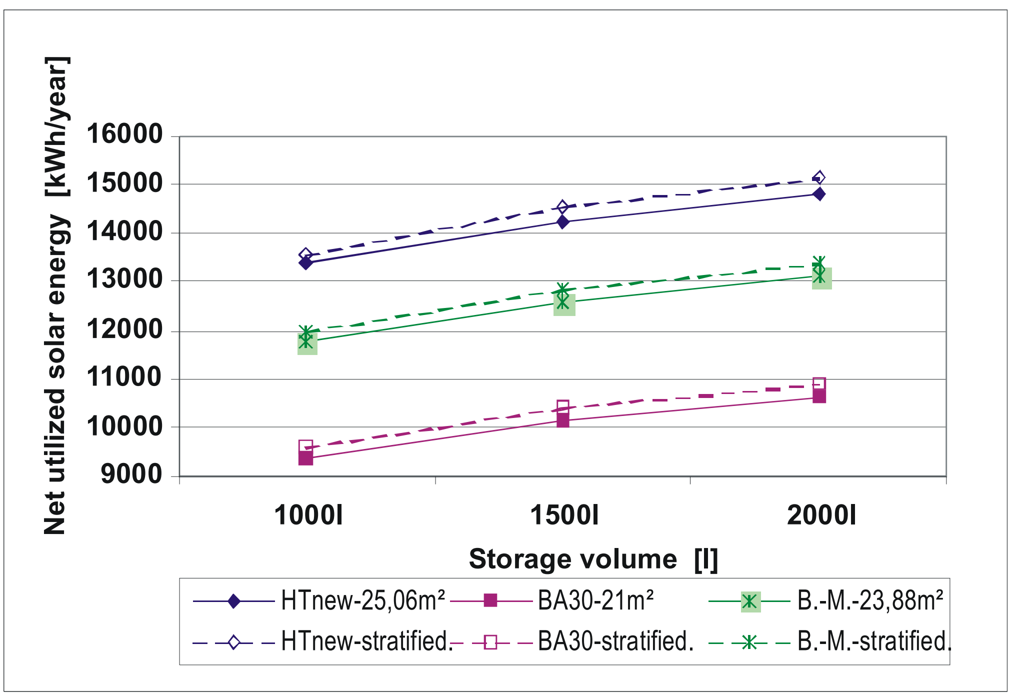

Figure 56: Net utilized solar energy of the solar heating system with about 20 m^2 different solar collectors as a function of the storage volume for a tapping profile of 4 m^3 for 5 days.

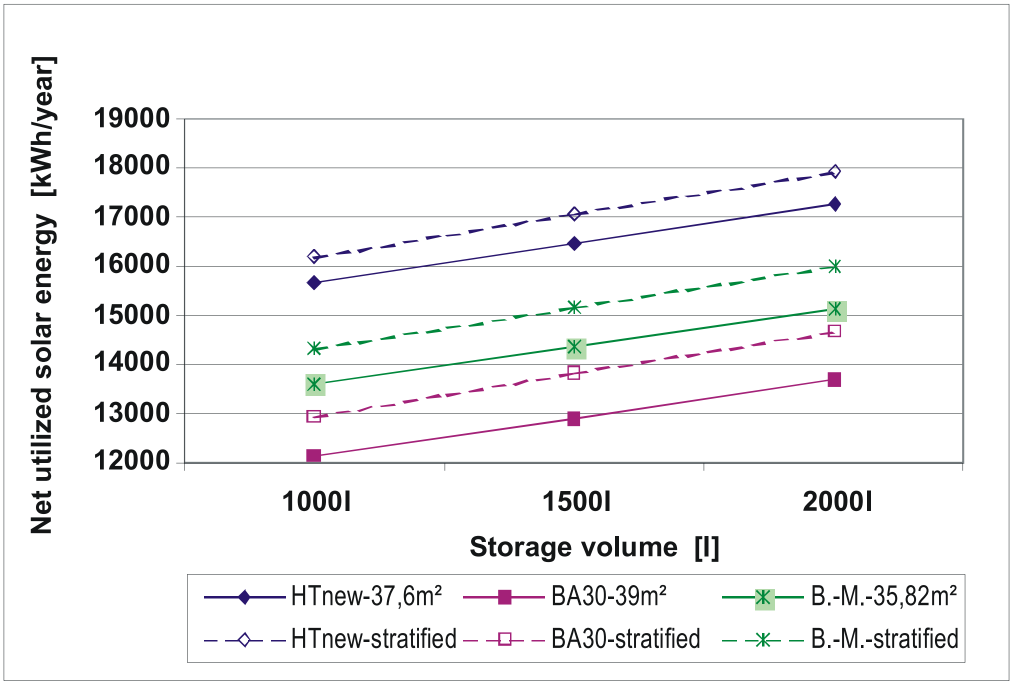

Figure 57: Net utilized solar energy of the solar heating system with about 40 m² different solar collectors as a function of the storage volume for a tapping profile of 2 m³ for 5 days.

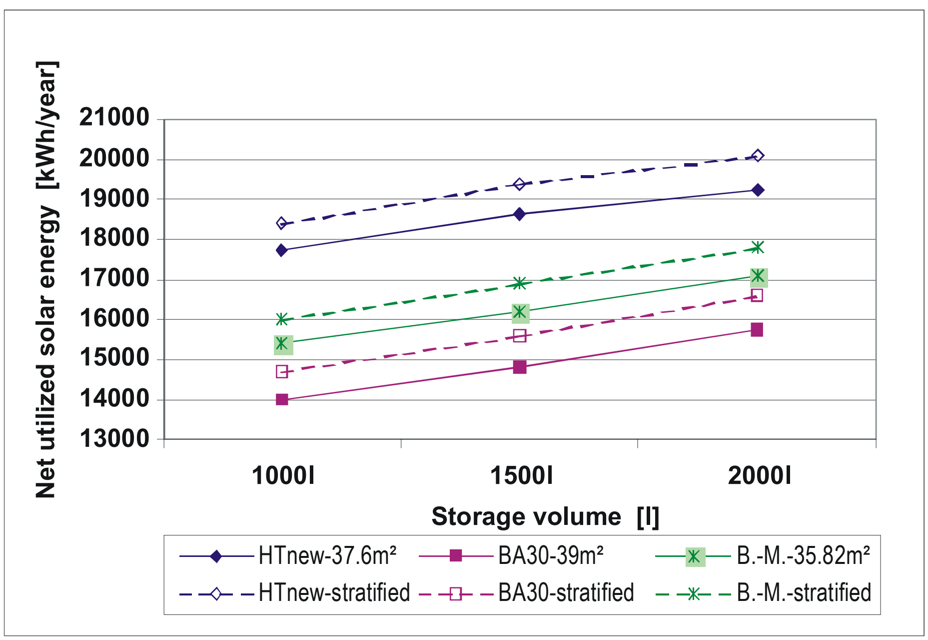

Figure 58: Net utilized solar energy of the solar heating system with about 40 m² different solar collectors as a function of the storage volume for a tapping profile of 3 m³ for 5 days.

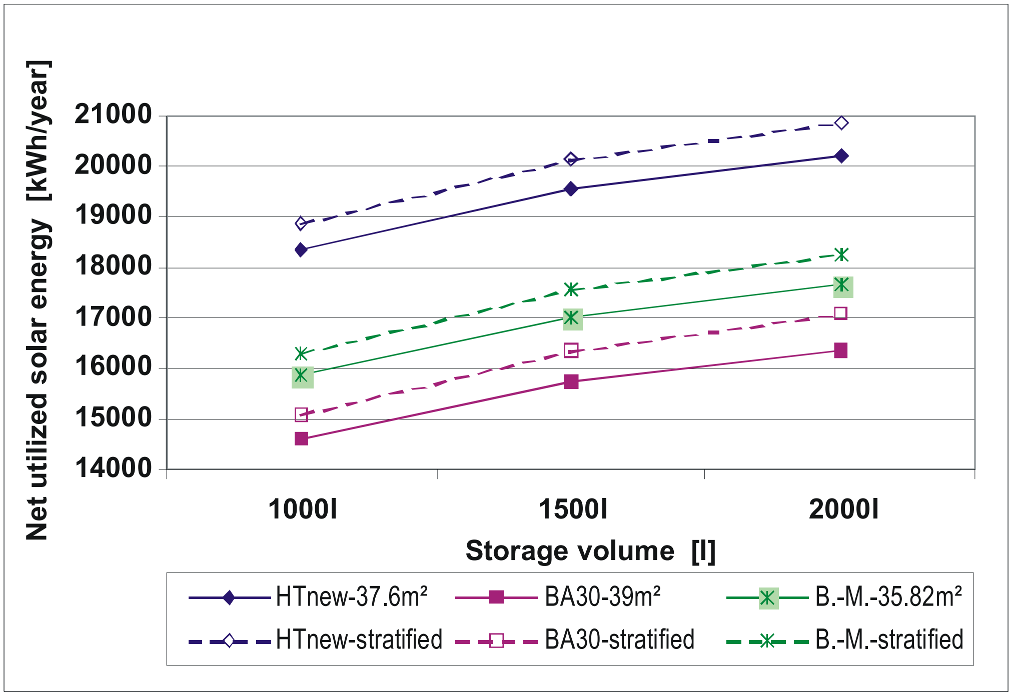

Figure 59:Net utilized solar energy of the solar heating system with about 40 m^2 different solar collectors as a function of the storage volume for a tapping profile of 4 m^3 for 5 days.

In figures 60 and 61, curves are outlined for the net utilized solar energy of the solar heating system as a function of the solar fraction (on an yearly basis). The only difference between the models for figure 32 and figure 33 is the inlet from the solar collector loop. The solar fraction is defined as the ratio between the net utilized solar energy and the heat demand, which is the sum of the hot-water consumption and the heat loss of the circulation pipe.
The figures show that the larger the solar collector area, the higher the solar fraction becomes, whereas the net utilized solar energy of the solar heating system per m^2 solar collector goes down.

Figures 62-64 illustrate how the thermal performance of the solar heating system is affected by the changes in the consumption pattern. The larger the consumption, the higher the thermal performance of the solar heating system becomes. The figures show that in all the cases, the new HT solar collector is by far the best with regard to performance. It can perform about 11% more compared to the Batec-Marstal solar collector and about 29% more compared to BA30. It appears from the graphs that for small solar collector areas, the difference between the performance per m^2 area for different solar collectors is not very great, whereas the difference increases with rising solar collector area.

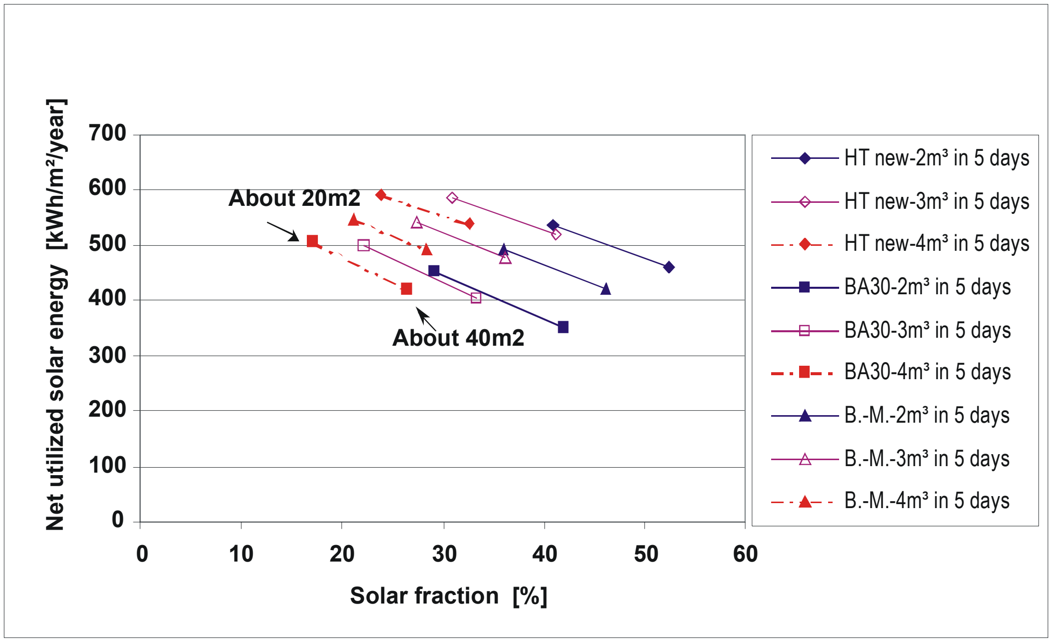

Figure 60: The net utilized solar energy of the solar heating system as a function of the solar fraction for different solar collectors and solar collector areas (2000 l storage with fixed inlet from the solar collector loop).

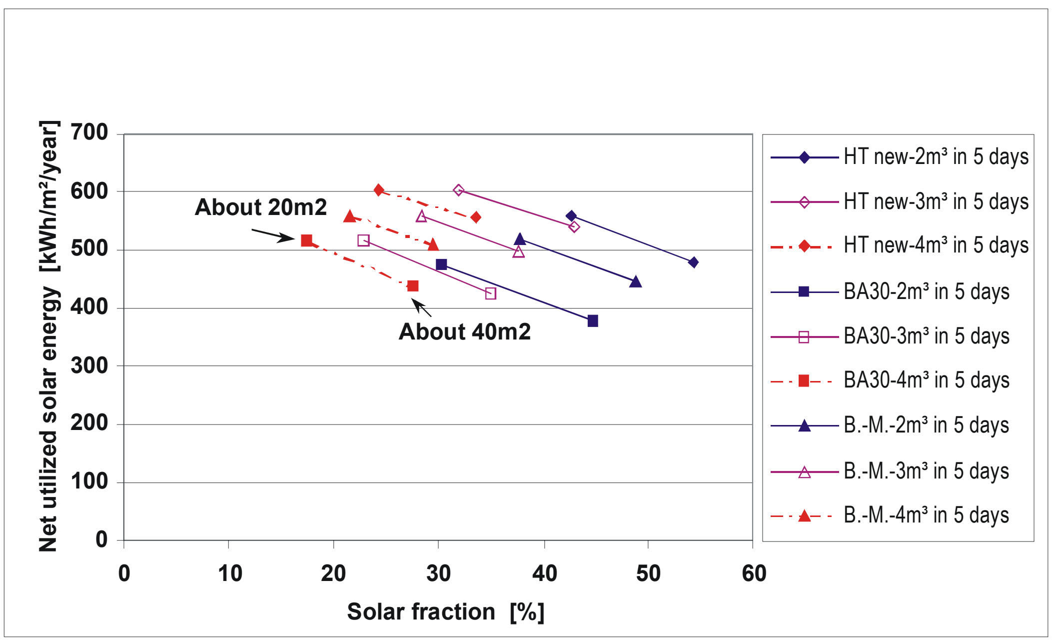

Figure 61: The utilized solar energy of the solar heating system as a function of the solar fraction for different solar collectors and solar collector areas (2000 l storage with stratified inlet from the solar collector loop).

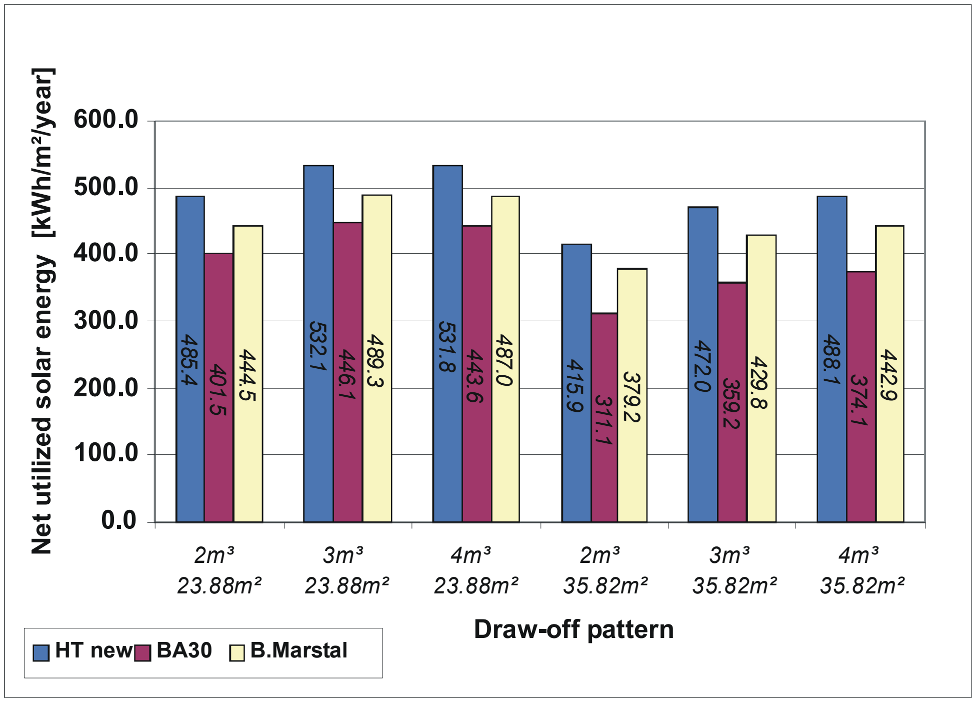

Figure 62: The net utilized solar energy of the solar heating system per m^2 solar collector as a function of the consumption pattern for different solar collectors with 1000 l storage.

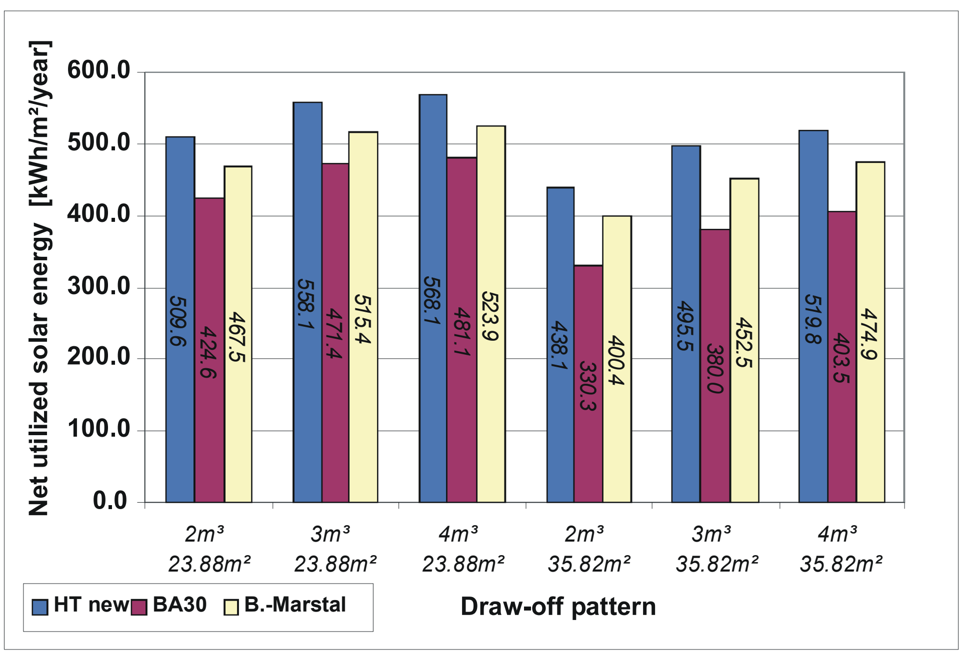

Figure 63: The net utilized solar energy of the solar heating system per m^2 solar collector as a function of the consumption pattern for different solar collectors with 1500 l storage.

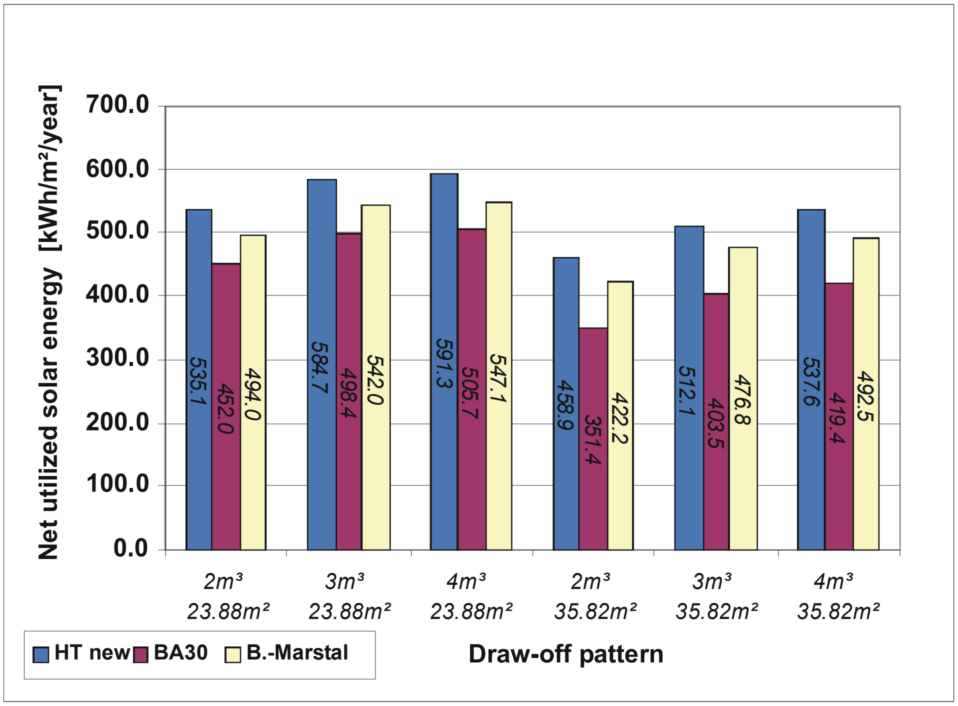

Figure 64: The net utilized solar energy of the solar heating system per m² solar collector as a function of the consumption pattern for different solar collectors with 2000 l storage.

4 Calculation of performances of the solar heating plant connected to the district heating system

To calculate the thermal performance of the solar heating plant that heats up water in the return loop of the district heating, an Excel spreadsheet is used. [7].

Calculations are made with the same four solar collectors as for the school and the kindergarten, see section 2.5. Solar collectors facing south, with a tilt angle of 45° are assumed. The results of the calculations are shown in figure 65. The figure shows annual solar collector performances as a function of the mean solar collector fluid temperature, which is kept constant throughout the year. The lower the mean fluid temperature in the solar collector is, the higher the solar collector performance becomes. The curve of the new HT solar collector lies higher than the others for all temperature levels, except from for the small mean fluid temperatures, where the BA30 solar collector is the best.

Here should be noted that the Batec-Marstal solar collector was tested at Danish Technological Institute with water as solar collector fluid, whereas the other solar collectors were tested with a 40% propylene glycol/water mixture. The thermal capacity of the water is higher than the propylene glycol/water mixture, which, among other things, is the reason why water is a better heat transfer medium. The solar collector efficiency is therefore greater if the water is used as solar collector fluid instead of the propylene glycol/water mixture. For that reason it is difficult to compare the performance of Batec-Marstal with the thermal performance of the other solar collectors directly.
For the solar heating plant the new HT solar collector results in the best performance.

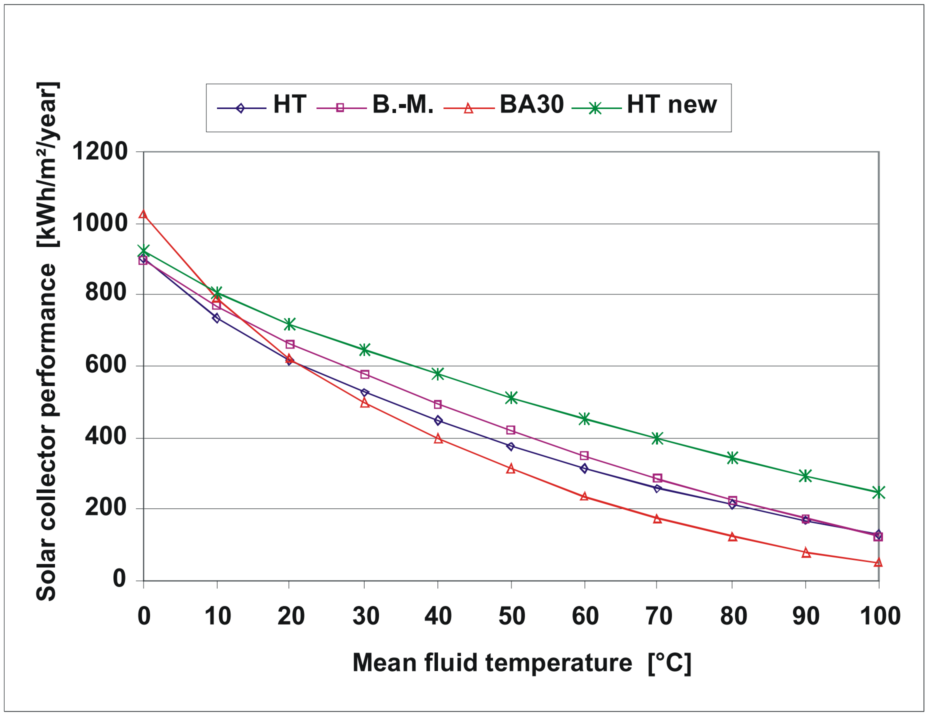

Figure 65: Solar collector performance per m^2 as a function of the mean solar collector fluid temperature.

5 Choice of solar heating systems and solar collectors.

Based on the calculations described in the previous sections and on estimates of the costs of the solar heating systems it was decided that two solar heating systems will be built: A solar heating system of about 35 m² for the school and a solar heating plant of about 120 m² connected to the district heating network.

Further, it was decided that the solar collectors for the school either should be 15 BA22 solar collector panels from Batec A/S or 15 ST-NA solar collector panels from Arcon Solvarme A/S, and that the solar collectors for the solar heating plant either should be 10 BA 120T solar collector panels from Batec A/S/Marstal VVS A/S or 10 new HT solar collector panels from Arcon Solvarme A/S.

The costs of the solar heating systems are determined by means of offers from Batec A/S, Arcon Solvarme A/S and a Latvian installer.
The net utilized solar energies of the solar heating system for the school were calculated with a 2000 l hot water tank with solar inlet stratifiers and with a daily hot water consumption of 2500 l in week days and no hot water consumption during week-ends, both with 15 BA22 panels and 15 ST-NA panels.

The costs, calculated net utilized solar energy and the cost/performance ratio for the systems based on the different solar collectors are given in table 19.

Solar collector field	Solar collector area [m²]	Net utilized solar energy [kWh/year]	Cost [DKK]	Cost/performance ratio [DKK/(kWh/year)]
15 ST-NA	37.5	16717	199743	11.9
15 BA22	32.9	13437	174733	13.0

Table 19: Costs and thermal performance for the solar heating system for the school.

The calculated thermal performance of the solar heating plant at a solar collector fluid temperature of 50°C and the costs of the solar heating plant are given in table 20.

Solar collector field	Solar collector area [m²]	Net utilized solar energy [kWh/year]	Cost [DKK]	Cost/performance ratio [DKK/(kWh/year)]
10 new HT	125	64050	295419	4.61
10 BA 120T	120	50400	319533	6.34

Table 20: Costs and thermal performance for the solar heating plant.

From the tables it is obvious that from an economical point of view the use of the solar collectors from Arcon Solvarme A/S is preferable.

6 References

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[4] ”Måling af solfangereffektivitet Batec A/S BA30”. Miroslav Bosanac and Inge-Lise Clausen. Prøvningsrapport D2117 A. Prøvestationen for Solenergi, TI, January 1997.

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