Energy savings from a compact and a large multi-family solar water heaters

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Abstract

Two hot water solar heaters (HWSH) are modeled using the simulation software Trnsys, the case study corresponds to the domestic hot water (DHW) needs of a 40 dwelling building in Paris, France. System designs are built in agreement to all physical and thermal restrains, and the objective is to obtain high energy savings with respect to a hot water electric heater. The compact HWSH uses a hybrid electric-solar tank to store the harvested solar energy in order to limit the occupied space in the cellar and to achieve a night thermal treatment of solar hot water avoiding bacteria formation. The large HWSH has a supplementary tank for the solar energy storage to optimize the energy savings. Both systems use a part of the useful solar energy via a heat exchanger to balance the heat loss of the circulation loop. If solar energy at high temperature is not available an auxiliary heater maintains the circulation loop at set-up temperature. The results show that by exploiting the solar energy, the designed compact and large HWSH could save electricity up to 21.7 MWh/y and 22.8 MWh/y, respectively, for the same DHW load. These savings represent respectively 20.5% and 21.6% of the total annual electric consumption of the standard system. The financial savings strongly depend on the energy price. In this paper, based on the relatively low price of electricity in France in 2009, the compact HWSH could save 1421 €/y and the large HWSH could save 1518 €/y.

1. Introduction

This paper focuses on two multi-family hot water solar heaters (HWSH) with conventional storage tanks and forced circulation solar loop. These installations provide hot water for a 40 dwelling building in Paris via a circulation loop running for 24/7. The annual energy and financial savings are computed with respect to the electric consumption of a standard water heater feeding the same load. First, the two new solar water heaters are designed and sized taking into account all physical and thermal restrains to meet the demand. Second, two models are build with Trnsys program and a numerical simulation is carried out to describe the system operation under given conditions. Finally, results are compared with a standard electric water heater, pointing out the energy and the financial savings.

2. System layout

2.1 Reference system: electric water heater

Due to an interesting electricity price, many buildings are equipped with electric water heaters having a large storage capacity to run only during the night. The main advantage of this system is that the domestic hot water (DHW) is produced through the night to take advantage of the low electricity price, the hot water is then stored in the three well-isolated tanks. The system is able to supply all consumers in the building without running out of hot water. The main setbacks on such a system are:

• The high temperature circulation loop runs continuously, generating important thermal loses and consuming a lot of electricity at high price. This continuous water circulation is a requirement of the thermal regulation in buildings.

• Even if the tanks are well insulated, the storage causes a supplementary heat loss and the already low performance of the system is reduced even more.

• Storage tanks and auxiliary loop heater occupy a large space, usually located in the basement of the building. Sometimes a room is designed to receive a standard system and little space remains available to add improvements (ex. one more tank).

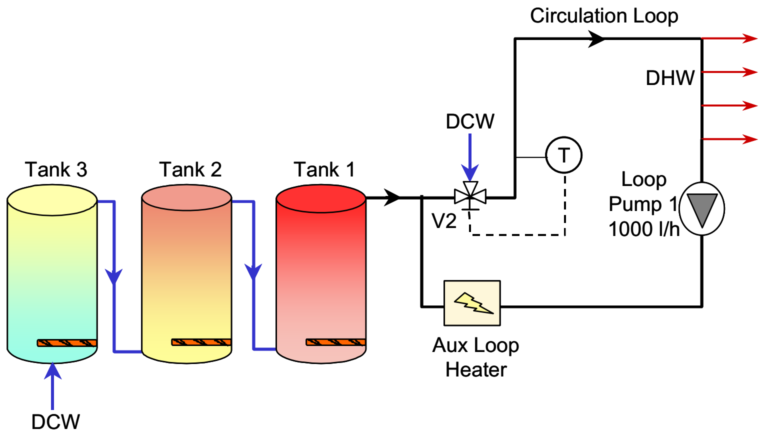

Fig 1. Standard electric water heater with three storage tanks, circulation loop and auxiliary loop heater.

System operation is relatively intuitive: the domestic cold water (DCW) replaces the hot water consumed, starting with tank #3 up to tank #1. The set-up temperature in all tanks is 65°C in order to compensate the thermal losses during the day and the temperature drop in the circulation loop. The thermal regulation in buildings demands a constant running circulation loop for hot tap water with a temperature above 50°C. In these conditions, no bacteria is developed in the hot water circuit and the consumers taps are fed almost instantly with hot water. The circulation loop is equipped with an auxiliary heater to maintain a high temperature in case of low consumption and a thermostatic mixing valve to add some DCW in case of strong demand. In normal operation, the auxiliary heater provides DHW up to 55°C especially during night time when consumption is low or nil and no hot water is coming from tank #1. The mixing valve adds DCW mostly during the day when the demand is high and the distribution loop is fed with hot water at 65°C from tank #1.

2.2 Compact solar water heater

The first solar system analyzed in this work is equipped with a hybrid solar-electric tank in order to minimize the occupied floor surface. Tank #3 is used to store DHW produced during the night by the electric element and the solar energy harvested by the collectors during daytime. The main advantages of this type of system are:

• The same three tanks are employed with both electric and solar energy and no additional storage is required for the solar energy.

• Early in the morning (starting at 7 am) an important hot water consumption empties a large part of tank #3 and makes possible the storage of the solar energy available soon after.

• Every night, the electric element in tank #3 heats up the entire volume to avoid bacteria formation. This system is appropriate for medical care buildings where hot water quality requirements are severe.

• The solar circuit can also be connected to a heat exchanger to heat up the circulation loop when the fluid temperature at the collector outlet exceeds the return temperature of the loop, here 50°C.

• Finally, this type of system can be put into practice upgrading an existing standard electric system without important changes or additional floor space requirement.

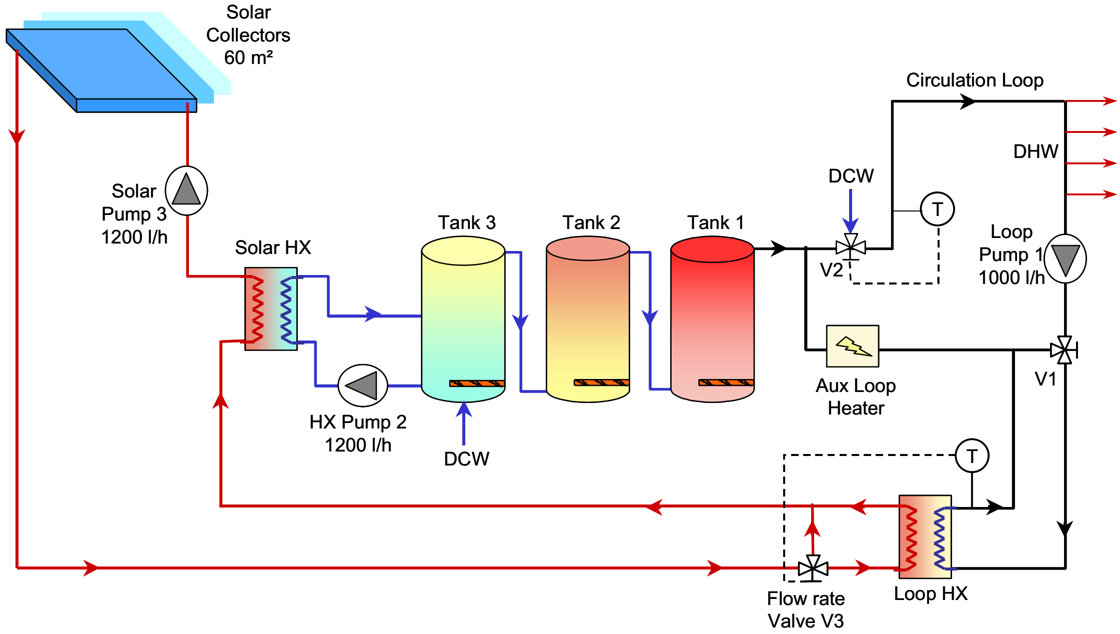

Fig 2. Compact solar water heater with a hybrid solar-electric tank and a heat exchanger (HX) between the solar circuit and the circulation loop.

When the fluid temperature in the solar circuit rises above 50°C, the circulation loop HX is put in operation to heat up the loop using solar energy. Flow rate valves V1 and V3 open to allow the direct use of solar energy avoiding the electricity consumption of the auxiliary heater. Valve V1 admits only on/off positions. Valve V3 is controlled to keep a constant temperature of 55°C at the HX outlet of the circulation loop. Solar pump 3 is put in operation whenever the solar energy can be used either in the circulation loop or in the storage tank. The HX pump 2 is running only if the heat carrier fluid has a higher temperature than tank #3 when the loop HX is used. In this way, solar energy can be used simultaneously or separately to heat up the circulation loop or tank #3.

2.3 Large solar water heater

The second solar system studied in this paper has four storage tanks: three electric tanks as in the standard system and a separate solar tank. In this way, more solar energy can be harvested and stored in tank #4, and to be used then depending on its temperature level. Consequently, the DHW needs can be off-phase with the resource; the solar energy is harvested whenever it is available and used later when needed. This system can be put in practice upgrading an existent standard electric system by adding a solar tank, if the room or the cellar permits it, with a minimum of hydraulic connections.

The solar energy is harvested by the collectors and stored into tank #4 via a HX. The solar pump 3 and the HX pump 2 are controlled to start at the same time with the same flow rate: 1200 l/h. Whenever DHW is poured, the solar energy migrates to tank #3 and so on. In the same time, if the temperature allows it, the solar energy of tank #4 is used to heat up the circulation loop through a HX. The circulation HX pump 4 is controlled to regulate the outlet temperature of the circulation loop at 55°C, as represented in figure 3.

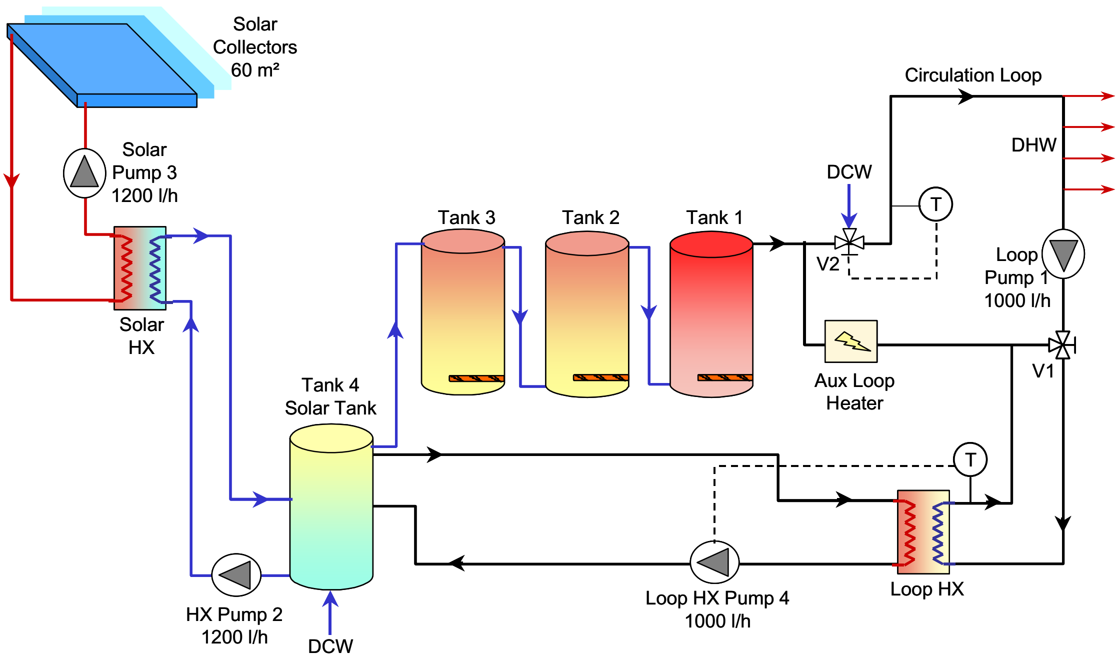

Fig 3. Large solar water heater with three electric tanks and a solar tank. The circulation loop HX is fed with solar energy from the solar tank #4.

3. Input data and controls

3.1 DHW pouring

The DHW consumption of a multi-family building presents high variations on seasonal and weekday bases, as already mentioned in other papers [1]. If the annual DHW demand is 1150 m^3/year, corresponding to an average of 3.15 m^3/day, the maximum and minimum values are significantly different:

- The maximum is reached in December when DHW demand rises up to 5.53 m^3/day.
- The minimum is attained in August with a demand going from 1.1 m^3/day to 1.64 m^3/day.

The monthly and weekly variations of the DHW consumption are given by the coefficients in table 1 applied to the average value:

Table 1. Monthly and weekly coefficients of the DHW consumption.

1	2	3	4	5	6	7	8	9	10	11	12
1.29	1.29	1.12	1.03	0.9	0.92	0.67	0.4	0.75	1.11	1.16	1.35

M	T	W	T	F	S	S
0.96	0.86	0.92	0.87	0.9	1.19	1.3

3.2 System hardware

The input data for the electric (table 2) and solar (table 3) tanks used in the Trnsys models are listed in the next tables [2]. All tanks, solar and electric, are modeled using 25 nodes per tank. Tanks #1 and #2 produce DHW during night time all year long, but tank #3 is shut down in July and August for a better adjustment of the DHW storage to the demand. The percents in the next tables represent volumetric parts.

Table 2. Electric tank input data.

Volume	2 m^3
Height	2.035 m
Ambient temperature	20 °C
DCW intake	1%
DHW outtake	100%
Electric heater elevation	10 % *
Electric heater power	20 kW
Set-up temperature	65°C
Heating time	22:00 – 6:00

Table 3. Solar tank input data.

Volume	2 m^3
Height	2.035 m
Ambient temperature	20 °C
DCW intake	1%
DHW outtake	100%
Solar intake	50 %
Solar outtake	1 %
Circulation loop intake	50%
Circulation loop outtake	100 %

* The electric heater is not placed at the very bottom of the tank to delay its cover up with scale build-up and postpone the maintenance events.

Solar energy is collected through 30 flat glazed collectors to assist the electric water heater of a 40 dwelling building. A slightly different collector sizing is used for single-family houses, higher specific area per dwelling or larger specific solar tank volume per m^2 of collector [3]. See input data for collectors in table 4.

Table 4. Solar collector input data.

Surface	60 m^2, 1.5 m^2/family
Flow rate	1200 l/h, 20 l/h/m^2
Heat carrier fluid	water + 30% glycol
Orientation	South
Slope	45°
Intercept efficiency	0.79
Efficiency slope	4.89 W/m^2K
Efficiency curvature	0.0138 W/m^2K^2

Input data of the circulation loop HX (table 5), solar HX (table 6), and auxiliary heater (table 7) are presented as follows:

Table 5. Input data for the circulation loop HX.

Hot fluid	Water
Circulation flow rate	1000 l/h
Hot fluid flow rate	Variable
Heat transfer flow	2500 W/K

Table 6. Input data for the solar HX.

Hot fluid	Water + 30% glycol
Fluid flow rate	1200 l/h
Hot fluid flow rate	1200 l/h
Heat transfer flow	2500 W/K

Table 7. Input data for the auxiliary electric heater on the circulation loop.

Heating power	9 kW
Set-up temperature	55°C
Loss coefficient	2.57 W/K
Ambient temperature	20°C
Heating efficiency	1

3.3 System software

The operation of solar pump 3 is controlled as a function of the temperature difference between the incoming hot fluid from the solar collectors and the tank temperature. In the case of the compact system, the tank temperature is registered at 25%, and in the case of the large system at only 15%. If ΔT is higher than 5°C, pumps 2 and 3 are put in operation and if ΔT is lower than 2°C the pumps are stopped. A security cut down of the solar circuit is operated if the upper temperature of the solar tank reaches 85°C. The use of the circulation loop HX is decided depending of the temperature difference between the inlet hot and cold fluids: if $\Delta T>5°C$ the HX is running or, if $\Delta T<2°C$ the HX is bypassed. Connections with the loop HX are different for each system:

• In the compact solar system V1 is fully opened for the circulation loop and V3 adjusts the solar fluid flow rate in order to provide only the heat needed to bring the circulation loop up to 55°C.

• In the large solar system V1 operates identically but on the hot side, the HX pump 4 drives the hot water with a variable flow rate to heat the circulation loop up to 55°C.

4. Results

4.1 Monthly performance

As shown in figures 4 and 5, the circulation auxiliary heater runs in a similar way for both solar systems on a monthly bases, with a little increase during summer.

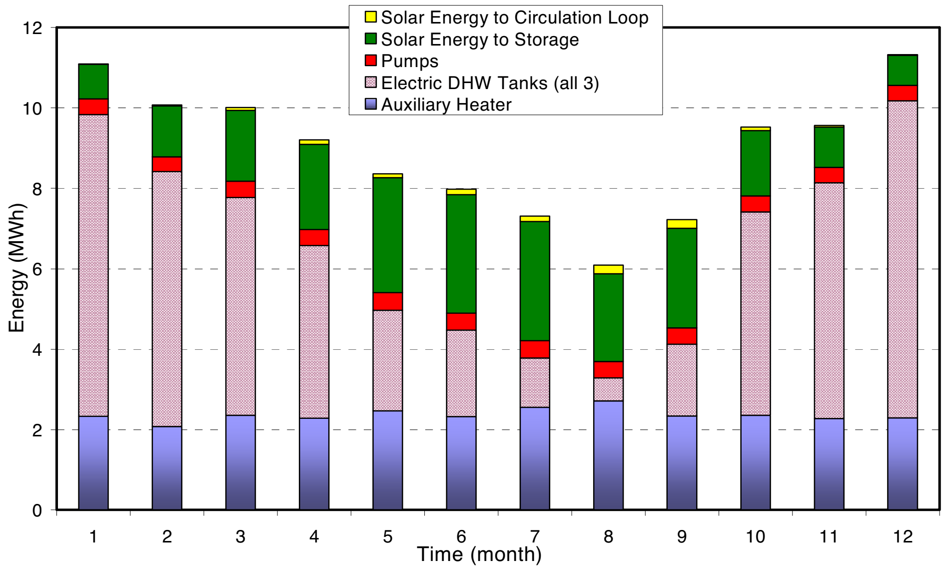

Fig 4. Electric and solar energy input to **compact** solar water heater.

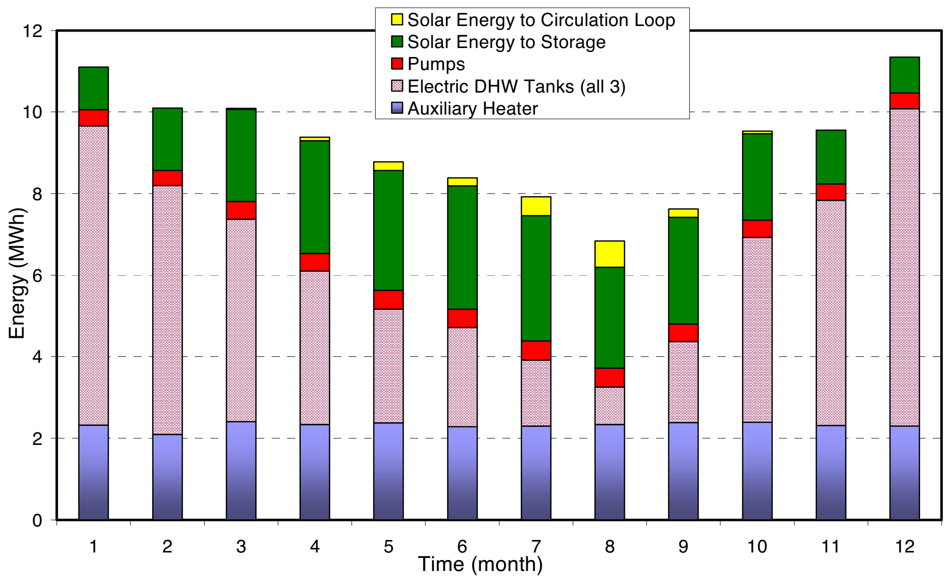

Fig 5. Electric and solar energy input to **large** solar water heater.

This is caused by the significantly undersized DHW needs which bring the circulation thermal losses to a higher quota and force the auxiliary heater to overcome these losses. In the cold season, the DHW pouring feeds the circulation loop with hot water from the tanks and the auxiliary heater runs especially at night. The high variation of the load is put forward by the tank electric consumption that drops from 7.9 MWh in December to 0.6 MWh in August for the compact HWSH and to 0.9 for the large one.

Solar energy to storage is almost identical in both systems with a maximum of 3 MWh in June and July and a minimum of 0.75 MWh in December for the compact HWSH and 0.87 MWh for the large one. The main difference is the solar energy use in the circulation loop which gets 0.64 MWh in August in the large HWSH and only 0.22 MWh in compact one. This difference decreases with decreasing available sun energy reaching zero from November to February. Values are found to be higher than for very large solar systems [4] and lower than for smaller solar system [5] both located in warmer and sunny regions.

4.2 Annual performance

Solar annual fraction *SF* is defined as the ratio between the solar energy production and the total energy input of the system (1). The solar energy E_{solar} is mainly used to produce DHW in storage tanks but also, in a smaller amount, to heat up the circulation loop. The total electricity consumption E_{elec} is the sum of three electric flows: auxiliary heater of the circulation loop, three storage tanks for DHW and pumps.

$$SF = E_{solar} / \left(E_{solar} + E_{elec}\right) \tag{1}$$

The DHW load is constant for all three heaters, 57.6 MWh/y. the annual energy savings are the difference between the total electricity consumed by the reference system and the compact or large solar heaters.

One can observe in table 8 that the compact HWSH obtains an annual energy saving of 21.7 MWh with respect to the reference system and the large HWSH saves up to 22.8 MWh. These savings represent 20.5% and 21.6% of the total annual electric consumption of a standard system which is 105.5 MWh. The energy saving difference between the two solar systems is relatively low regarding to the 2000 l storage increase for the large solar system. Nevertheless, tank #4 is able to increase the solar production up to 26.04 MWh but it amplifies also the thermal losses of system. Finally, the large HWSH becomes oversized especially with respect to the summer DHW needs and a larger share of the available solar energy cannot be efficiently used.

Table 8. Solar production, electric consumption and energy savings of the compact and large solar WH with respect to the reference system.

			Electricity				
	Solar fraction (%)	**Solar production (MWh)**	**Auxiliary heater (MWh)**	**DHW tanks (3) (MWh)**	**Pumps (MWh)**	**Total consumption (MWh)**	**Energy savings (MWh)**
Reference electric WH	0	0	29.49	73.38	2.63	105.5	0
Compact HWSH	22.07	23.74	28.35	50.84	4.81	83.8	21.7
Large HWSH	23.95	26.04	27.84	49.74	5.12	82.7	22.8

4.3 Financial savings

The energy savings brought by the solar production can be easily converted into financial savings by multiplying with the fuel price of MWh [6]. Nevertheless, the electricity price in France varies a lot with the season and depends also on night and day time. To compute the annual financial savings, the electricity consumed has to be accounted on seasonal and day/night bases. In these conditions, the compact HWSH has a **1 421** €/y saving and the large HWSH has a **1 518** €/y saving. The annual electricity cost for the heating and DHW of the 40 dwelling building with standard electric water heater is 7 162 €/y. One can notice an important economy for both solar systems despite the low price of electricity, especially during summer (table 9).

Table 9. Electricity prices in France for an average multi-family building during night (22h-6h) and day (6h-22h) [7]. Prices including VAT.

		Price ç€/kWh
Warm season	Night	3.208
April to Sept.	Day	4.353
Cold season	Night	8.84
Oct. to Mars	Day	12.881

5. Discussion and conclusion

This paper presents two HWSH with different designs: a compact one with a hybrid solar-electric tank designed to fit into a room sized after an electric water heater, and a large one with a supplementary solar tank able to store as much solar energy as can be harvested. Both solar systems are compared with a standard electric heater designed for a 40 dwelling building located in Paris, France.

One can conclude that the large HWSH with a slightly better solar fraction presents a better efficiency than the compact one. However, the large HWSH saves 22.8 MWh/y of electricity compared to 21.7 MWh/y for the compact one, this difference has to be put in contrast with the additional space required for the larger system. Moreover, the compact HWSH is appropriate for medical care buildings (ex. hospitals, nurseries, hospices) due to the fully hot water stock treatment to stop bacteria development. Additionally, when computing the annual financial savings, considering the electricity price for this size of buildings in France, the compact solar system saves only 6.5% less than the large one, 1421 €/y versus 1518 €/y respectively (VAT included). Nevertheless, the savings obtained in these cases are very small due to the low electricity price.

In the present study all pumps employed are standard old models presenting an important electric consumption (ex. 300 W). These can be replaced by the latest A class pumps with permanent magnetic rotor, which consumes approximately 40% less for the same head.

References

[1] Thur A., Furbo S., Shan L.J., 2006, Energy savings for solar heating systems, Solar Energy 80, 1463-1474.

[2] Klein S.A., Trnsys version 16, 2004, Solar Energy Laboratory, University of Wisconsin-Madison, Website: <http://www.ashrae-mtl.org/text/f_ashrae.html>.

[3] Hobbi A., 2009, Optimal design of a forced circulation solar water heater system for a residential unit in cold climate using Trnsys, Solar Energy 83, 700-714.

[4] Chow T.T., Fong K.F., Chan A.L.S., Lin Z., 2006, Potential application of a centralized solar water-heating system for a high-rise residential building in Hong Kong, Applied Energy 83, 42-54.

[5] Prapas D.E., Veliannis I., Evangelopoulos A., Stiropoulos B.A., 1995, Large DHW system with distributed storage tanks, Solar Energy 55, 175-184.

[6] Pedersen P.V., 1993, System design optimization for large building integrated solar heating system for domestic hot water, Solar Energy 50, 267-273.

[7] EDF, Electricity prices for multi-family buildings more than 36 kVA starting on August 15, 2009, Web: <http://collectivite.edf.fr/fichiers/fckeditor/File/EDF_collectivites/CGV/Tarifs_Jaunes_aout_2009.pdf>.