SYSTEM SIMULATION OF A NEW CENTRAL SOLAR HEATING PLANT WITH A SEASONAL DUCT STORAGE IN GENEVA

Daniel Pahud[1], Jean-Christophe Hadorn[2], Charly Cornu[3] and Stéphane Commend[4]
[1]ISAAC-DACD-SUPSI, IBPSA-CH Board, Lugano, Switzerland, daniel.pahud@supsi.ch
[2] Base Consultants SA, Geneva, Switzerland, jchadorn@baseconsultants.com
[3] BG Ingénieurs Conseils SA, Lausanne, Switzerland, charly.cornu@bg-21.com
[4] GeoMod Ingénieurs Conseils SA, Lausanne, Switzerland, scommend@geomod.ch

ABSTRACT

A central solar heating system with seasonal storage (CSHPSS) is foreseen for e new residential project in Geneva, involving a central ground duct store in the system concept. A case study is performed with a TRNSYS simulation tool to simulate the overall system thermal performances and perform a pre-optimisation of the system main components, taking into account economical aspects. An existing simulation tool of such a system is used and further developed to take into account various heat distribution networks with various fluid temperature levels. In this paper the TRNSYS simulation tool is presented together with the case study and the obtained results.

INTRODUCTION

Nine new residential buildings are planned in Florence square in Geneva's suburb. The owners' desire is to use as much as possible renewable energies to meet the building's thermal requirements. In order not to miss an important opportunity in the energy development strategy of the county, Geneva State Energy Office (ScanE) would like to study a more global solution such as the selling of solar heat whose financing would be independent from the buildings' one. Large collector areas and seasonal heat storage in the ground would be involved. Large scale effects are expected with the coupling of existing public buildings in the neighbourhood. It is also an advantage as there would be sufficiently available room for the solar collectors.

As a result, the Geneva State Energy Office has commissioned a feasibility study to establish an energy concept involving a central seasonal ground heat storage, simulate the system thermal performances, perform a pre-optimisation of the system components and assess the project economical aspects.

The TRNSYS thermal simulation software (Klein S. A. et al., 2005) has been used for the thermal analysis of the system. This study takes the benefice of experiences gained in the development of TRNSYS simulation tools of such systems (Pahud, 1996; Dubach and al., 1999) and applied to a similar project (Pahud, 2003).

THE FLORENCE PROJECT

The central solar heating system with seasonal storage (CSHPSS) has to be designed for 4 different types of consumers. There are each characterised with different energy profiles and heat distribution temperature levels. Available room for solar collectors is also different for each consumer and the proportion between maximum possible collector area and annual heating requirements is not the same for each of them. Size, energy requirements, heat distribution temperature levels and maximum possible solar collector area are listed in table 1 for each consumer.

The total annual energy requirement, assessed to 5'000 MWh, is large and very favourable for a CSHPSS's system. Nevertheless the heat distribution temperatures are very different from one consumer to the other. The new Florence and Champendal buildings, planned according to a low energy standard, can be heated with a maximum forward fluid temperature below 30°C. The Florence and Emile Gourd schools are existing buildings and require much higher temperatures. Florence school will be retrofitted, which explains the lower forward fluid temperature of 50°C relatively to the Emile Gourd school one, set to 65°C. Furthermore, hot water proportion relatively to space heating is also very different between residential and school buildings.

The system concept has to take all of these aspects into account. The best solution has to be found with disseminated solar collector fields, a unique central ground heat store and different heat distribution levels.

Table 1
Principal characteristics of the four different heat consumer types

TYPE OF CONSUMER	FLORENCE BUILDINGS	CHAMPENDAL BUILDINGS	FLORENCE SCHOOL	EMILE GOURD SCHOOL	TOTAL
Heated floor area	34’900 m^2	26’100 m^2	11’600 m^2	18’800 m^2	91’400 m^2
Annual space heating requirements	620 MWh	560 MWh	720 MWh	1’630 MWh	3’530 MWh
Forward/return heating fluid temperature[1)]	28°C/24.8°C	30°C/26°C	50°C/40°C	65°C/50°C	
Annual hot water requirements	720 MWh	540 MWh	80 MWh	130 MWh	1’470 MWh
Distributed hot water temperature	60 °C	60 °C	60 °C	60 °C	
Total annual thermal energy requirements	1’340 MWh	1’100 MWh	800 MWh	1’760 MWh	5’000 MWh
Total peak power load	670 kW	540 kW	450 kW	800 kW	2’460 kW
Maximum possible collector area	980 m^2	480 m^2	6’300 m^2	3’800 m^2	11’560 m^2

[1)] the forward and return fluid temperatures are calculated for a design outdoor air temperature of -6°C in Geneva. The requested forward fluid temperature is then decreasing with an increasing outdoor air temperature.

THE SYSTEM CONCEPT

The system concept is based on the decentralisation of the subsystem components. Each building will have its own collector field, auxiliary boiler and water tanks for solar gains and hot water. Only the ground duct storage will be centralised. All the buildings will be coupled in parallel to it. In order to take benefice of the lowest return fluid temperature, two heat distributions per building are foreseen: one for space heating and one for domestic hot water (DWH). Particular attention will be paid to ensure the lowest possible return fluid temperature. Return fluid temperature from the DHW should be below 20°C. A first elaboration of the system concept per building is shown in figure 1. It will be studied more in detail in the next phase of the project.

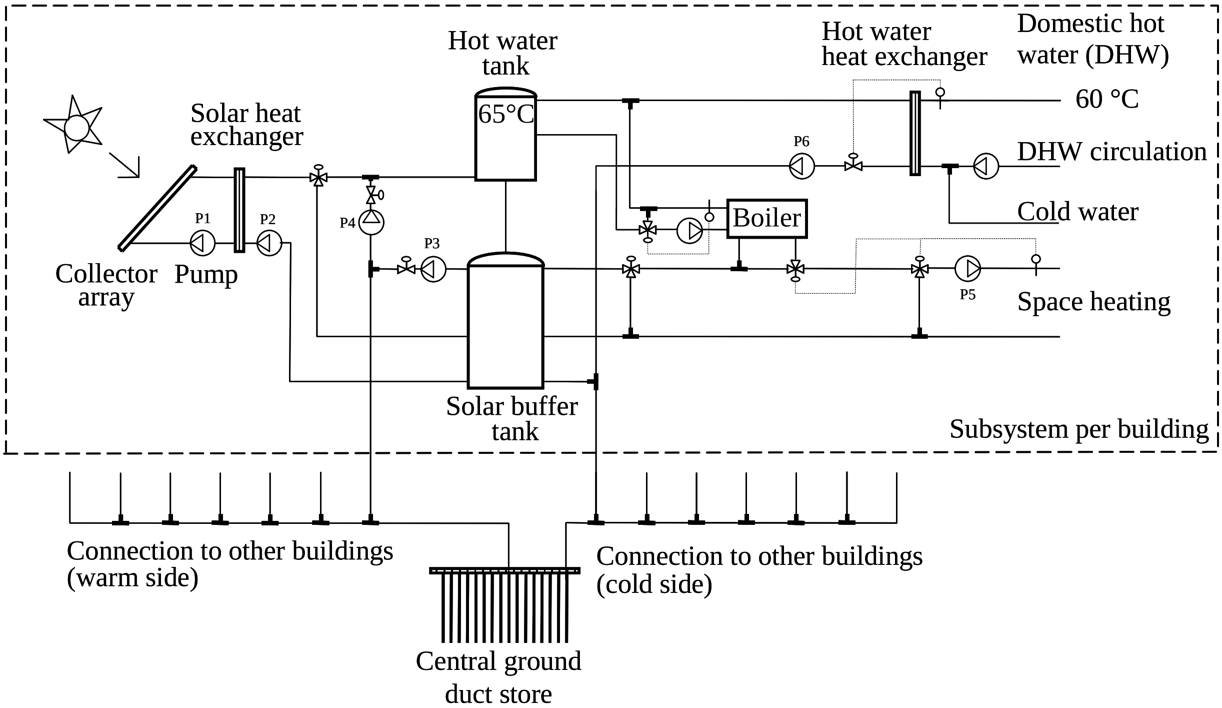

Figure 1 : System layout per building. Only the seasonal ground duct store is centralised

SIMULATION TOOL

TRNSYS is a well-known and widely used system simulation programme of transient thermal processes (Klein et al., 2005). This programme, chosen to develop a simulation tool of a CSHPSS system, provides libraries of subroutines that represent, for example, the components of typical solar energy systems (such as solar collectors, water tanks, pumps, pipes, valves, controllers, etc.). The CSHPSS's system layout shown in figure 2 has been developed and validated in other studies (Pahud, 1996; Pahud, 2000; Pahud, 2003). It was further developed to allow the user to define up to four different heat distribution networks. The TRNSYS tool is using non standard TRNSYS components. For the system main parts they are:

- the solar collector component TYPE 252, based on the Matched Flow Collector model, developed at the Royal Institute of Technology in Sweden (Isaksson, 1995). It has the advantage to take into consideration a quadratic temperature dependence of the overall loss coefficient, as well as the heat capacitive effects of a solar collector field.
- the water store component TYPE 274, developed at the ITW of Stuttgart University in Germany (Druck and Pauschinger, 1994). TYPE 274 is chosen for the possibility of handling up to five flow loops (or hydraulic circuits) connected to the tank.
- the duct store component TRNVDSTP, developed at Lund University in Sweden (Hellström, 1989; Pahud and Hellström, 1996), and further developed at the EPFL Lausanne (Pahud et al., 1996). This component is devised for the simulation of thermal processes which involve thermal energy storage in the ground, including a ground heat exchanger that can be a borehole field. It has been used and /or validated in numerous studies; see for example Chuard and al. (1983) or Pahud (1993).

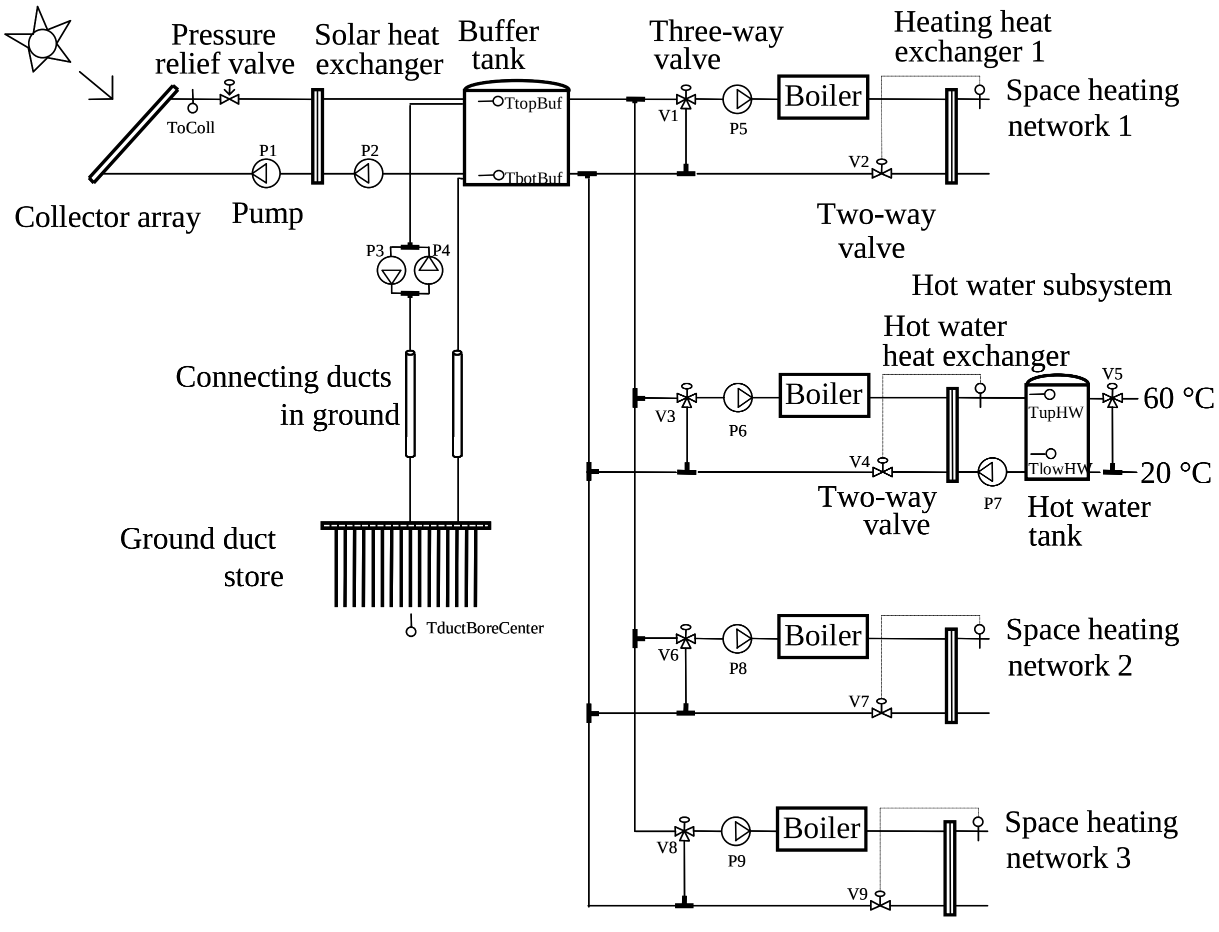

Figure 2 : System layout of the system simulated with the TRNSYS tool

A short time step of 7.5 minutes is chosen to ensure that the thermal interaction between the different subsystems is carefully taken into account. The simulations are performed over a long period of time (12 years), so that the transient effects of the first years (heating of the ground duct store) are included in the system's overall energy balances and thermal performances.

Only one collector field and one short term buffer tank can be simulated. Equivalent parameters are calculated from all the collector fields and water tanks, on the basis of their areas, volumes and thermal properties. Heat losses of the pipe connections between the buffer tanks and the ground duct store are taken into account. The four heat distribution networks are used to take into account the various temperature levels. The hot water distribution subsystem is defined for domestic hot water requirements of all the buildings. The three remaining space heating distribution networks are used for low space heating temperature by grouping together the Florence and Champendal residential buildings, average space heating temperature for the Florence school and high space heating temperature with the Emile Gourd school. The parameters of the space heating heat exchangers are set as if they were inexistent, as foreseen in the real system.

Thanks to the system layout concept shown in figure 2, each subsystems can be operated independently with optimum conditions. This also make the system control simpler and easier to understand and implement.

Solar collector array control

An on/off controller with dead-band temperature differences controls the two pumps P1 and P2 of the collector subsystem. The two fluid temperatures ToColl and TbotBuf are compared. The flow rate in the collectors is set to a constant value when available solar gains are collected. A pressure relief valve limits the outlet fluid temperature from the solar collectors to 100 °C. A stratified charge of the buffer store is performed.

Ground duct store control

The operation of the two ground store pumps P3 and P4 is controlled with on/off controllers. Only one pump can be run at a time, depending on the loading or unloading operation mode of the ground store. The flow rate is adjusted to preserve as much as possible the vertical temperature stratification in the buffer store. In the loading mode, heat is transferred from the buffer store to the ground store. Water is taken at the top of the buffer store, pushed through the ground heat exchanger and re-enters at the bottom of the buffer store. In the unloading mode, the other pump is used, resulting in reverse fluid circulation. In this operation mode, heat is transferred from the ground store to the buffer store.

Heat distribution control

Each distribution network has a the three-way valve (V1, V3, V6 or V8), which permits the disconnection of the heat distribution subsystem from the solar part of the system, when the fluid temperature at the top of the buffer store is lower than the return fluid temperature from the heat exchanger. The inlet temperature on the primary side of the heat exchanger can not fall below a value which is shifted by some Kelvins (set to 5K) relative to the requested outlet fluid temperature on the secondary side. If necessary, the boiler is used to raise the fluid temperature to the desired value. The heat exchanger is a counter-flow heat exchanger whose UA-value depends on the maximum heat rate to be transferred and also on the above mentioned temperature shift. The two-way valve (V2, V4, V7 or V9), controlled by the forward fluid temperature on the secondary side of the heat exchanger, reduces the flow rate on the primary side as much as possible, thus making the lowest return fluid temperature to the buffer store possible. The maximum flow rate on the primary side of the heat exchanger must be greater than the maximum value on the secondary side. The pump is switched off if the heat demand is null.

As a result of the system concept and control, all the short term storage requirements are performed by the buffer tank. The ground heat storage is only ensuring the long term energy storage requirements. It has been shown that the overall efficiency of the system is slightly better if the ground storage is only loaded when the top temperature of the buffer store is larger than 65°C, the required water temperature for the preparation of domestic hot water.

SIMULATION PROCEDURE

The thermal characteristics of the subsystems are set, as closely as possible, to correspond to typical values of the foreseen components. Top quality single glazed flat plate collectors are simulated. Hourly profiles of the thermal energy requirements are calculated with the help of weather meteorological values for Geneva and a simple load model set to reproduce the annual energy requirements and the maximum peak power loads. This model, developed by Pahud (1996), is part of the simulation tool.

The best system design has to be found with the boundaries fixed by the project. The total collector area is fixed to a reasonable value of 9'200 m^2. The collectors are assumed to be tilted towards south with a 20° inclination. The volume of the water buffer tank, sized in relation to the collector area, is fixed to a slightly small value of 80 litres/m^2. The ground duct store may not be deeper than 30m, so that the double-U pipe borehole heat exchangers will not penetrate an aquifer that lies below. The top layer is formed by humid siltish clay containing some gravel.

Table 2
Cost data for the main solar subsystem components

Solar collectors (per collector unit area)		1'000 CHF/m^2
Buffer store (per tank unit volume)		1'000 CHF/m^3
Ground store	top part (per top store unit area)	320 CHF/m^2
	borehole heat exchanger (per bore unit length)	100 CHF/m

The thermal properties of the ground have been determined with a thermal response test. The average ground thermal conductivity is assessed to 1.9 W/(mK) and the initial ground temperature to 12 °C. The top side of the ground store will be well insulated.

Simple cost functions for the main solar subsystem components, listed in table 2, were defined. They are used to determine the total investment cost of the solar part of the system. The solar annual cost is then calculated with an annuity factor of 0.07, including operating and maintenance cost.

Once all the system parameters are fixed a simulation is performed. The average annual solar heat delivered in the distribution networks over its lifetime, set to 25 years, is assessed. It is including the cold start of the ground storage.

The average annual solar heat and solar annual cost are used to establish the system **solar fraction** and **solar cost**. They are respectively the fraction of the total annual heat demand met by solar heat and the cost of solar heat. An optimal system is searched as the one that can provide the maximum solar fraction at the least solar cost. The ground store volume and the borehole number are varied for this scope.

SIMULATION RESULTS

The ground store volume is varied from 20'000 to 120'000 m^3 and the borehole number from 100 to 900. The results are mapped in a "solar cost versus solar fraction" diagram (cf. figure 3).

The **economical design optimum** is obtained with 500 boreholes of 30 m each and a spacing of 2.2 m, making a ground storage volume of 70'000 m^3. With a total collector area of 9'200 m^2 and a total volume of 730 m^3 for the short term water buffer tanks, the total investment for the solar part of the system is 12 MCHF. The system ensures a solar fraction of 68% with a solar cost of 250 CHF/MWh. This heating energy cost is comparable to oil heating cost that resulted from the recent peak oil price.

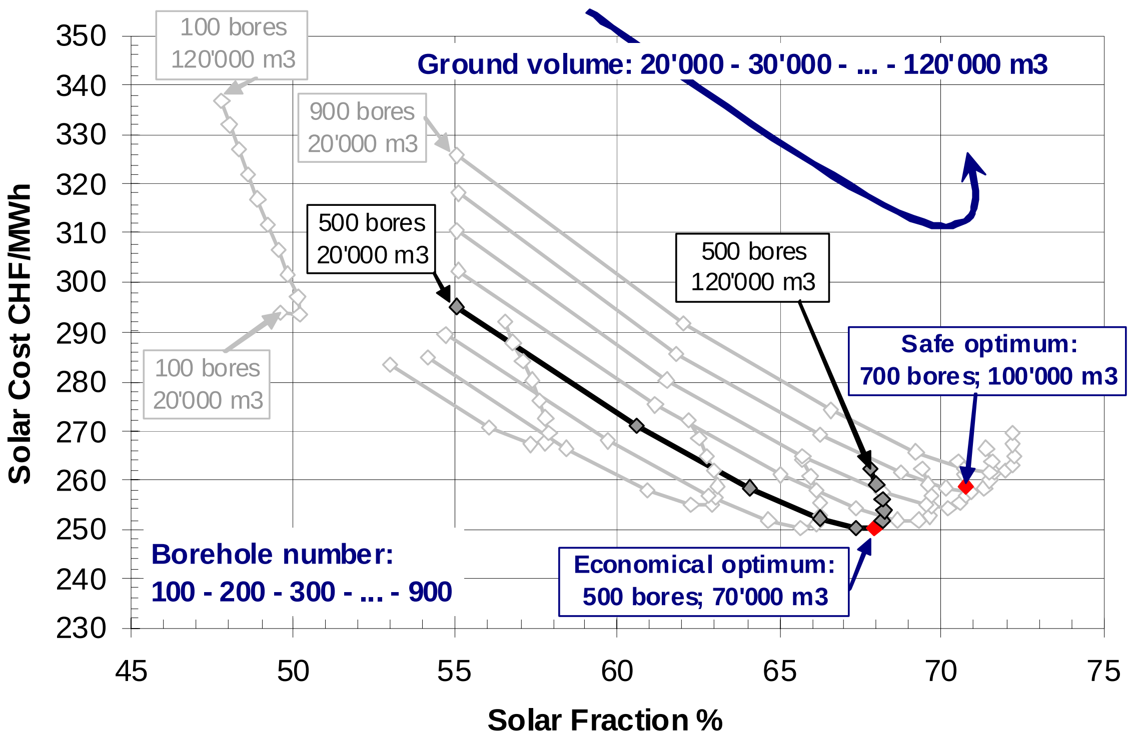

Figure 3 : Solar cost in function of the solar fraction. The economical optimum, for a given collector area, is the system that presents the lowest solar cost

With the economical design optimum the fluid temperature in the collectors exceeds sometimes 100°C during normal system operation. This may cause recurrent overheating problems, which would limit system reliability and reduce its life time. In order to avoid these problems, a safe design optimum is searched for, which would guarantee no overheating problems during normal system operation.

The **safe design optimum** is obtained with 700 boreholes of 30 m each and a spacing of 2.2 m, making a ground storage volume of 100’000 m^3. The total investment for the solar part of the system is 13 MCHF (+7% relative to the economical optimum). The system ensures a solar fraction of 71% with a solar cost of 260 CHF/MWh (+4% relative to the economical optimum).

The design characteristics and thermal performances of the two variants are listed in table 3.

The solar fraction of the economical variant is calculated to 68% as an average over the life time of the system and for all the buildings. The Florence and Champendal buildings, taken alone, have a space heating solar fraction as large as 98% and a domestic hot water one of 77%. As a result, the overall solar fraction for these buildings is calculated to 87%. The solar fraction of the two schools is rather smaller, 61% for the Florence school and 44% for the Emile Gourd school. It clearly demonstrates the importance of having the possibility to distribute heating energy at the lowest possible temperature.

CONCLUSION

The results of this pre-study are positive and proved the technical and economical feasibility of the CSHPSS’system. The annual thermal energy requirement to be covered amounts to 5’000 MWh, which is equivalent to the heat requirement of about 250 families. An overall solar fraction of 70% can be reached. The solar cost is comparable to oil heating with the recent price of 1.5 CHF/litre. The project will be studied more in details and should proceed. All practical aspects from financing to realisation will be closely investigated for an optimal project planning.

Table 3
Design characteristics and thermal performances of the two design variants

	ECONOMICAL DESIGN OPTIMUM				**SAFE DESIGN OPTIMUM**			
Annual heating demand	5’000	MWh			5’000	MWh		
Solar collector area	9’200	m^2 –	1.8	m^2/MWh	9’200	m^2 –	1.8	m^2/MWh
Buffer store volume	730	m^3 –	80	litre/m^2	730	m^3 –	80	litre/m^2
Ground store volume	70’000	m^3 –	7.6	m^3/m^2	100’000	m^3 –	10.9	m^3/m^2
Borehole vertical extension	30	m			30	m		
Borehole spacing	2.2	m			2.2	m		
Total borehole length	15’000	m –	1.6	m/m^2	21’000	m –	2.3	m/m^2
Annual solar heat	3’400	MWh			3’540	MWh		
Ground store cost	2’270	kCHF	19	%	3’170	kCHF	24	%
Buffer stores cost	730	kCHF	6	%	730	kCHF	6	%
Solar collectors cost	9’200	kCHF	75	%	9’200	kCHF	70	%
Total cost	12’200	kCHF	100	%	13’100	kCHF	100	%
Annual solar coll. efficiency	33	%			35	%		
Ground store efficiency	79	%			78	%		
Solar fraction	68.0	%			70.7	%		
Solar cost	250	CHF/MWh			259	CHF/MWh		

ACKNOWLEDGMENTS

The Geneva State Energy Office (ScanE), the project promoters, buildings owners and architects are highly acknowledged for their initiative and support. The intention of Geneva's Industrial Services company (SIG) to support the project in future is greatly acknowledged. Finally, our special thanks to everybody who contributed to this project and the pre-study.

REFERENCES

Chuard P., Chuard D., Van Gilst J., Hadorn J.-C. and Mercier C. (1983) The IEA Task VII Swiss project in Vaulruz: design and first experiences. International conference on subsurface heat storage in theory and practice. pp. 195 – 206. Swedish Coucil for Building Research.

Druck H. and Pauschinger T. (1994) Multiport Storage-Model for TRNSYS. Version 1.5, November 1994. Institut für Thermodynamik und Wärmetechnik, Stuttgart University, Germany.

Dubach W., Fuchs H., Hartmann P., Juzi H., Wanner H., Wellauer R. and Pahud D. (1999) Saisonale Speicherung von Sonnenenergie im Erdboden zur Wärmeversorgung von grösseren Überbauungen. Schlussbericht, BFE-Project 18'543, Bern, Schweiz.

Hellström G. (1989) Duct Ground Heat Storage Model, Manual for Computer Code. Department of Mathematical Physics, University of Lund, Sweden.

Isakson P. (1995) Solar Collector Model for Testing and Simulation. PhD Thesis, Building Services Engineering, Royal Institute of Technology, Sweden.

Klein S. A. et al. (2005) TRNSYS. A Transient System Simulation Program. Version 15.3. Solar Energy Laboratory, University of Wisconsin, Madison, USA.

Pahud D. (1993) Analyse énergétique de l'immeuble industriel "Marcinhès" à Meyrin (GE). Thèse n° 2645. GAP, Section de Physique, Univ. de Genève. Atelier d'impression de la Section de Physique.

Pahud D. (1996) Simulation of Central Solar Heating Plants Using a Duct Store: an Application for Switzerland. Swiss grant Nr: 8220 – 042846. Department of Mathematical Physics, Lund Institute of Technology, Lund, Sweden.

Pahud D. (2000) Central Solar Heating Plants with Seasonal Duct Store and Short Term Water Store: Design Guidelines Obtained by Dynamic System Simulations. Solar Energy, Elsevier Science Ltd, Vol. 69, No 6, pp. 495-509.

Pahud D. (2003) Central Solar Heating Plant with a Seasonal Storage (CSHPSS) at Heumatt, Zürich Seebach. Analysis and design by dynamic system simulations. SUPSI – DACD – LEEE, Lugano, Svizzera.

Pahud D. and Hellström G. (1996) The New Duct Ground Heat Model for TRNSYS. In Proceedings of Eurotherm, Physical Models for Thermal Energy Stores, 25-27 March, pp. 127 – 136. Eindhoven, The Netherlands, A.A. van Steenhoven and W.G.L van Helden (eds).

Pahud D., Fromentin A. and Hadorn J.-C. (1996) The Duct Ground Heat Storage Model (DST) for TRNSYS Used for the Simulation of Heat Exchanger Piles. User Manual, December 1996 Version. Internal Report. LASEN - DGC- EPFL, Switzerland.