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SOLAR-ASSISTED HEAT PUMP SYSTEM AND IN-GROUND ENERGY STORAGE IN A SCHOOL BUILDING

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Abstract—An experimental solar-assisted heat pump system with a hybrid ground-coupled storage at the F.U.L. in Arlon, Belgium, is described. It includes a 382 m^2 solar roof, two types of water storages, heat storage in earth by horizontal exchangers, and heat pumps. One operating period (1984–1985) is analyzed. The data processed has shown that each of the subsystems has apparently performed adequately: annual collector efficiency is 0.41, heat pump C.O.P. range around 4. Despite important energy losses from the underground storage, the storage efficiency reaches 0.7. This effectiveness is mainly due to heat recovery below natural soil temperature and also to the use of buried tanks for short-term storage. The main difficulties are controlling the flow between these subsystems and developing an operating strategy that matches both the building's heat requirements and a good solar fraction.

1. INTRODUCTION

For several years now, work has been done in Europe toward incorporating active solar systems into the home. This concern is backed by the importance of the domestic sector in the E.E.C. energy balance and the size of its external energy deficit. This is particularly clear in the case of Belgium where the home takes up 40% of energy consumption and where the energy balance deficit has grown from 1 to 10% of the G.N.P. in the last 30 years.

Experiments show that the most active solar systems for housing are uneconomical without storage as they only work for a short period, corresponding to about a third of the annually available solar energy. There is, therefore, a lot of interest in developing storage systems enabling the solar energy acquired during the summer to be used in the winter.

Various systems of this kind have been thought up. They usually make use of solar technology and heat pumps. Hybrid systems based on storage in earth (clay, sand, rocks) or in underground tanks have been built and tried in several European countries. Much work is currently being undertaken in a number of countries in the world on various aspects of SAGCHP (Solar Assisted Ground-Coupled Heat Pumps). Substantial research in this area is also being supported by both the International Energy Agency (I.E.A.) and the Commission of the European Communities (C.E.C.).

A widespread desire has been expressed for an exchange of information between experts that would highlight the advances already made. Workshops and conferences have been organized covering a wide range of storage concepts such as storage in caverns, pits, aquifers, lakes and tube systems in soil and bedrock[1–4]. Givoni has given an overview of underground long term solar energy storage[5]. Svec et al.[6] have carried out an excellent review of the historical background, particularly concerning ground heat exchangers. Good manuals relating to thermal energy storage are available[7,8] and many reports of IEA (task VII: Central Solar Heating Plants with Seasonal Storage) are available.

All this work confirms the interest in seasonal storage but also points out remaining uncertainties and deficiencies. In spite of research efforts having produced valuable results, continued follow-up during the operating stage of real size designs is essential to confirm the technology and its economics, and to provide a basis for further improvements.

This article describes the experiment at the Fondation Universitaire Luxembourgeoise (F.U.L.), the only project of its kind in Belgium. After choosing the main characteristics of this large-scale project, we explain the difficulties of putting it into practice and making it work. We then give our first results and comment on them in light of models and theoretical estimates made.

2. DESCRIPTION OF THE EXPERIMENT

The hybrid solar-assisted heat pump system linked to an underground storage described here is at Arlon, Belgium (Fig. 1), 25 km west of Luxemburg (latitude: 42°41′N; longitude: 5°49′E; altitude above sea level: 416 m).

The system was designed in 1977 and was finished being built in 1983. It is intended for the air conditioning of two buildings with a total heated volume of 6600 m^3. The theoretical heat load is about 1100 GJ. In practice, once reduced heating days are deducted (weekends and holidays), the heat load comes to 900 GJ per year. For an average year, this load is shared as shown in Table 1. The design peak demand is about 148 kW of which 35 is for natural room ventilation and 21 is for mechanical room ventilation for outside/inside conditions of $-14°C/+19°C$. A schematic overview of the system is given in Fig. 2.

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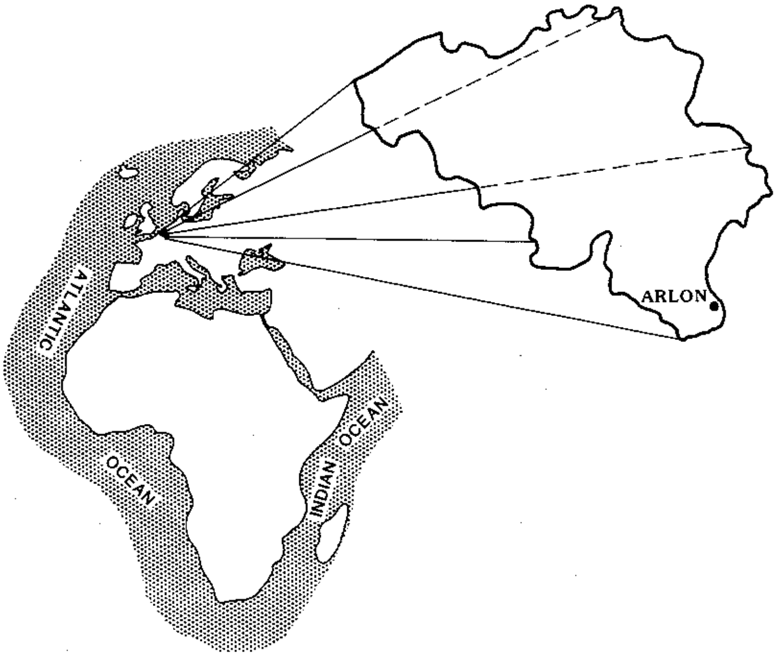

Fig. 1. Localization of Arlon in Europe.

2.1 *Solar collectors*

A total area of 382.4 m^2 of integrated solar collectors is shared between three roofs leaning 42°30′ and 90° from horizontal and facing south (N 180° E) and southeast (N 23° E and N 43° E). These collectors have a low fluid content (less than 0.6 dm^3/m^2) and use a mixture of water and propylene glycol. The absorber is made up of copper tubes brazed onto a copper plate covered by a chromium oxide selective surface. Collector data are the following:

aperture area	1.047 m^2 or 1.993 m^2 (two models)
optical efficiency ($F_R\tau\alpha$)	0.74 at 600 W/m^{-2}
heat loss coefficient (F_RU_L)	4.76 $W/m^{-2}K^{-1}$ at 600 W/m^{-2}

The nominal flow rate is about 60 $dm^3/h.m^2$, but this can be adjusted continuously up to about 200% of this value.

Table 1. Share of the heating load for an average year

January	17.9%
February	15.9%
March	13.4%
April	9.4%
May	3.3%
June	0.3%
July	0.0%
August	0.0%
September	1.7%
October	7.7%
November	13.6%
December	16.8%

2.2 *Heat storage in water*

Heat is stored experimentally in water in 10 insulated metal tanks buried 5 m deep, which make up a sensible heat storage volume of 500 m^3. Another 100 m^3 metal tank in an outhouse near the two other buildings is used as a buffer for short-term storage. Both storage volumes are linked up to the solar collector circuit via water to water heat exchangers. One of these tanks is insulated entirely with 0.16 m thick polyurethane, but the nine others are not insulated at the bottom, allowing a thermal flux toward the surroundings.

2.3 *Heat storage in earth*

We used 2500 m^3 of clay-rich earth mixed with sand for heat storage. Two layers of horizontal heat exchangers are buried one above the other at 1.5 m and 5.0 m deep. Each is made up of two different types of synthetic piping (EPDM). The first type of exchanger consists of 255 m of 19 mm inner diameter pipe with a spacing of 0.5 m between each tube. The second one, in the same level, is made up of 20 covers (8.5 m × 1.1 m), each with 60 pipes of 5.2 mm inner diameter bound together by fins, thus making a total area of 187 m^2 per level. The storage volume is insulated above and around the top of its sides with 0.16 m thick polyurethane and is lined with 1.5 mm thick plastic sheeting. The soil moisture is kept ideal (50% R.H.) for the heat exchangers via an automatic moistening system.

2.4 *Heat pumps*

Two sets of water-to-water and glycol–water-to-water electric heat pumps installed in the outhouse

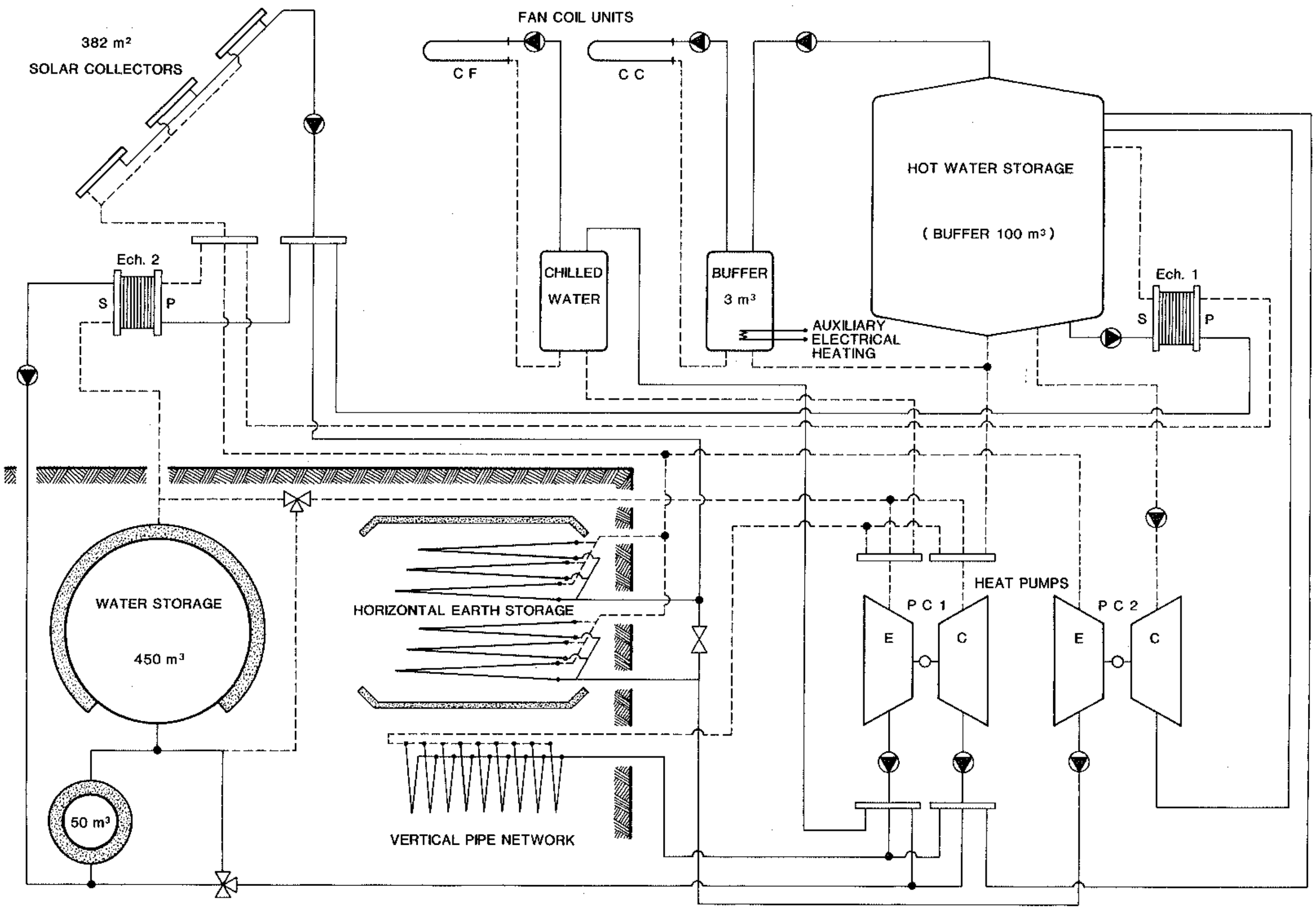

Fig. 2. Simplified schematic representation of the heating plant.

use these two large storage volumes as cold sources. The first set is split into two 110 kW units (condenser) and uses the heat from the water tanks. The second set has a 148-kW condenser and is linked up to the earth storage. The former is also used in reverse mode for air conditioning. In this case, a further warm source made up of a network of 42 vertical wells with double loops to 8 m deep may be used. Main heat pump characteristics are summarized in Table 2.

2.5 *Monitoring and control*

The whole heating plant is supervised by an automatic control system ensuring regulation, management, work optimization and scientific monitoring. An 8-bit microcomputer interfaced with an industrial smart interface and some peripherals is programmable in PL.I language. Four times an hour, the operational working modes and the values of 99 temperatures (platinium resistors), 19 flowrates (diaphragms), 4 solar radiations (pyranometers), and 4 electrical powers (instantaneous wattmeters) are stored on a floppy disk.

This data is then transferred to the central computer for further treatment. Twenty-six megabytes of information is available every year. The micro computer is also justified for control purposes, due to the complexity of the heating system: 4 storage modes, 8 discharge possibilities, 2 heat pumps, 3 solar roofs, 2 buffer tanks, 1 electrical backup heating, 13 circulating pumps, 3 air conditioning systems, and 28 motorized valves.

An analysis of hydraulic diagrams, energy needs, and irrational and incompatible possibilities has pointed out 16 working modes: 3 for summer cooling, 3 for solar energy storage, 2 for energy recovery from horizontal earth exchangers and 1 from vertical pipes, 3 for discharging from buried water tanks, 2 for mixing between water buffer tanks, 1 for direct distribution from buried tanks, and 1 for a backup heating system. The control software is modular and can be improved in the light of experience.

Table 2. Main heat pump characteristics

Part	Water/water heat pump	Glycol–water/ water heat pump
Condenser		
Heat capacity (kW)	220.5	147.3
Water temperature (°C)	47/52	47/52
Water flowrate (m^3/h)	19.0	25.4
Evaporator		
Cooling capacity (kW)	150.8	97.4
Fluid temperature (°C)	9/5	9/5
Fluid flowrate (m^3/h)	32.5	21.0
Electrical compressor		
Type	Semihermetic	Semihermetic
Operating power (kW)	58.8	44.0
Refrigerant	R22	R22

2.6 *Miscellaneous*

The energy is distributed throughout the buildings with air convectors via a 3-m^3 tank where an extra 100-kW electric heater may be used. Note that this power is lower than the amount calculated. Also notice that the storage system is far too small if considered only for seasonal use. A simple calculation for a single cycle and a recovery performance of unity shows that the energy extracted at the heat pump condensers hardly covers a quarter of the building's heat requirement. The planner's concept in 1977 was to experiment with seasonal storage rather than to build a correctly sized heating system.

3. OPERATING PRINCIPLES

When the sun shines, priority is given to transferring the energy collected in the roof to the water and earth storage. The initial idea of first filling the 100-m^3 tank was dropped because it is important to get maximum efficiency from the collectors. This may be achieved during the summer by heating the underground storage volumes that are at a low temperature after the heating season, which is more efficient than keeping the 100-m^3 storage tank at temperatures as high as 50° for no purpose. On the contrary, during the heating season, the 100-m^3 accumulator is rapidly cooled, and, when there is sufficient sunshine, it may efficiently be used with the collectors for intermediate storage. When heating is needed, the underground storage volume is used directly if its temperature is above that required by the convectors (i.e. 32°C). If this is not the case, this temperature is reached in the 100-m^3 tank via heat pumps.

Various operating modes are possible according to the source used and its temperature. Whenever possible, this operation takes place at night when electricity rates are cheaper. During part of the heating season, the energy accumulated in the buffer tank is sufficient to meet the day's requirements. When necessary, additional heating is provided in the 3-m^3 tank. An operating strategy has progressively been developed for organizing the system according to the 16 possible modes as a function of numerous parameters such as climatic conditions, storage temperatures, the building's heat requirements, etc. In each of the three solar collector circuits, the flowrate may be adjusted from 0 to 200% of the nominal rate. During the first year, the pumps ran at the top rate as soon as insolation reached 400 W/m^2 in the plane of the collectors.

This limit was experimentally deduced and takes into account the high power of these pumps (10 kW).

A 3-K temperature differential was applied between the collector circuit and the storage so as not to discharge the latter. All these operating modes need perfecting in light of the results and experience acquired and with respect to further plans.

4. SYSTEM PERFORMANCE

4.1 *Period in service*

The F.U.L. system experienced the difficulties of a complex system designed as a R & D project, but built and operated as an actual heating system. During the first operating period 1983 to 1984, some modifications had to be applied to the managing procedures, as well as to monitoring equipment. The mass flowrates in the collector circuits were not correctly estimated because the meters were ill suited to the actual flow rates. Leakages appeared in the underground piping. The readings from the temperature probes in the ground storage were then disturbed when the electrical connections were damaged by a digging machine. Consequently, much attention has to be paid to data processing and performance indications are only obtained after much delay. We have analyzed the system's behavior during the year from June 1, 1984 to May 31, 1985. Table 3 summarizes the climatic conditions on site during that year. Solar energy was mainly stored during the months of June, July, and August 1984 and May 1985.

The heating system was used from late September 1984 until early May 1985. The temperature during the end of January and during February 1985 was extremely low, but insolation was higher than normal. From then until late April, the underground tanks were used for the short-term storage of solar energy.

The evolution of insolation in 1984/1985 is typical of the Belgian climate, but with nearly a one-month lead: the winter drop in insolation arises often in October instead of September and the spring increase is usually present in March and not in February. However, the energy levels are quite normal.

4.2 *Solar collectors*

Figure 3 shows the energy balance of the collector system in 10-day steps with the temperature level of fluid at the collector inlet and the ambient air temperature. The light part of the diagram shows total irradiation in the plane of the 382-m^2 of collectors. The dark part of the diagram shows the amount of energy actually received from the collector subsystem, as given by the data acquisition system.

Table 3. Climatic conditions on site during year analyzed

Average outdoor temperature	8.2°C
Minimum outdoor temperature (January 1985)	−18.0°C
Maximum outdoor temperature (July 1984)	32.2°C
Degree-days 15/15	2680.9°C day
Solar energy—horizontal plane	3218 MJ/m^2

Total incident solar energy is 922 GJ for the year and net collected energy is 375 GJ, which gives a mean annual yield of 0.41. However, if we only take into account the period when the collectors were really active (solar power rate greater than 400 W/m^2), the yield approaches 0.80. Notice that total incident solar energy (922 GJ) would be just enough to heat the buildings if there were no yield problems and no dephasing between supply and demand. Furthermore, no significant difference in yield was observed between roofs of different orientation.

4.3 *Heat storage in the ground*

As mentioned, priority was given to storage in the ground rather than in the 100-m^3 storage tank. During the period considered, heat was stored simultaneously in the 500 m^3 of water and in the earth whenever the control system judged the transfer worth doing (i.e., as mentioned before, when the 400 W/m^2 insolation threshold is reached and a minimum 3 K temperature differential is present between the collector circuit and the buried tanks).

Toward the end of the storage period (August–September), whenever the net heat input to the tanks was not felt to be sufficient, our strategy was to stop storing in water and to use only the buried heat exchangers.

During the heating season, we mainly used the water tanks. We did this for two reasons: first, 9 out of the 10 buried tanks are only insulated on top (160 mm of polyurethane), and this leads to a serious heat loss through the bottom of the tanks, which are directly in contact with the ground. Delaying the use of heat stored in the tanks might have meant losing the advantage of having stored heat during the summer; second, heat exchange between the soil and the pipes turned out to be too slow to meet the building's heating requirements fast enough. This is probably because of a faulty automatic moistening system.

Figure 4 shows the temperature variation as a function of time in the water tanks (average temp.), in the earth storage (typical temperature, in the middle of the volume, 0.20 m under the upper exchanger level) and in the ground outside the storage area. The water tanks reacted quite rapidly to heat input and reached about 37°C at the end of the storage period.

The sharp drop in temperature toward the end of September is due to both heat loss through the soil and to discharge via the heat pumps. The water temperature oscillations observed between the end of January and the end of June are due to the use of the buried tanks for short-term storage. The earth surrounding the buried heat exchangers reached 30°C, but never dropped below about 15°C through lack of use, as discussed above. The slow temperature variation outside the storage area shows heat conduction through the ground.

The phenomena surrounding heat storage in the ground is being studied in greater depth during the 1985 to 1986 period. The temperatures measured in various places are being compared to those obtained

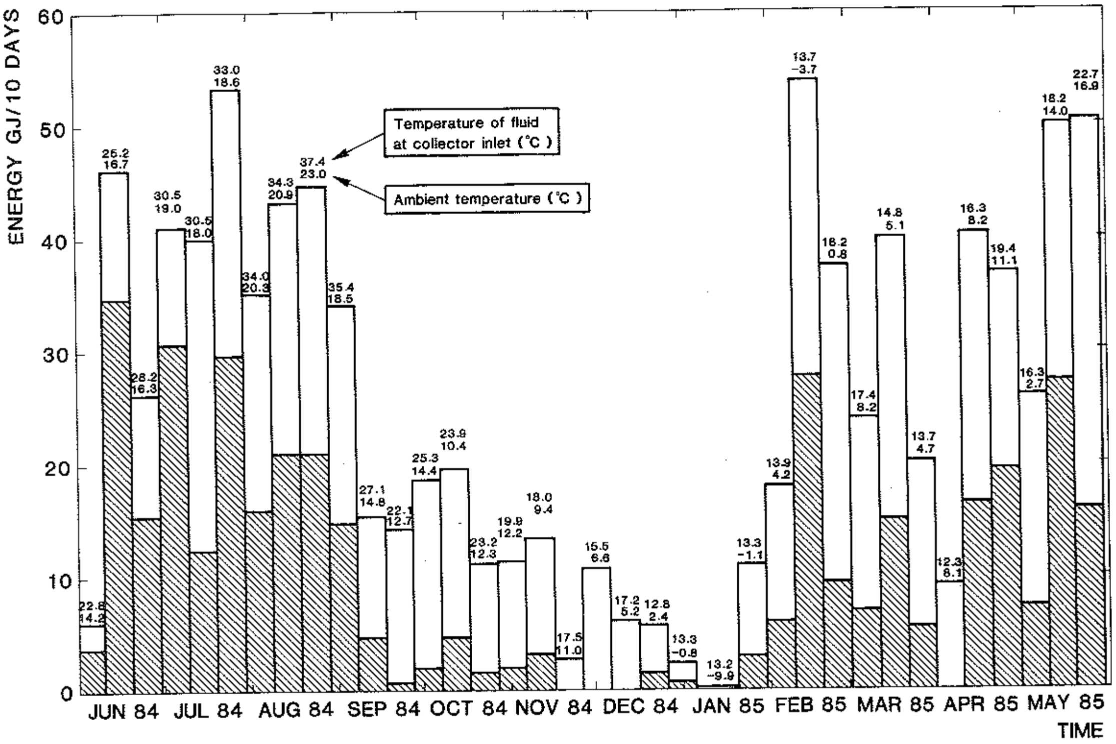

Fig. 3. Energy balance of the collector system in 10-day steps with temperature levels.

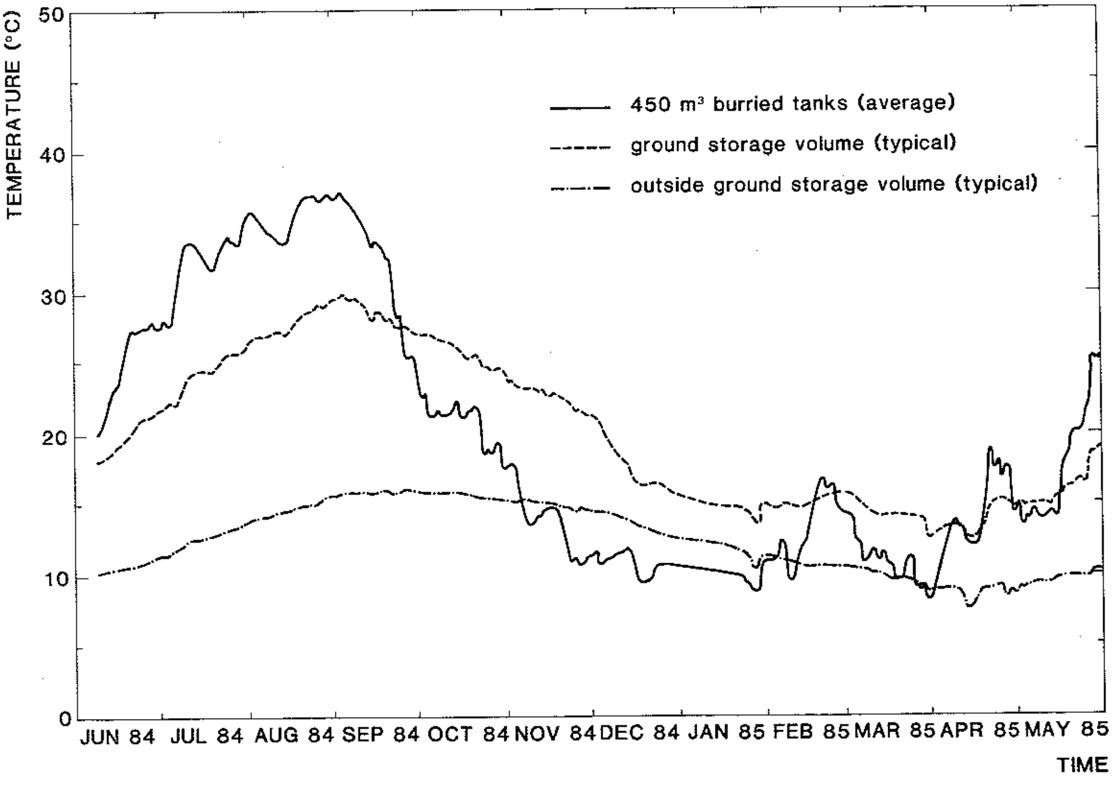

Fig. 4. Temperature evolution in the storage.

via a numerical model and the results will soon be available.

The intensity of the heat loss through the bottom of the tanks is confirmed in Fig. 5, which compares the solar energy input minus the heat pump extraction in the nine partially insulated water tanks with their variation in sensible heat content. It proves that in spite of a continuous input of heat into the storage, net seasonal storage in the water tanks is virtually nil. From these results, it is not necessarily inferred that the technological solution is wrong. Operating the heat pumps in winter has demonstrated that at low water temperature (in the range of 8°C), useful heat is progressively recovered through the tanks, which act as a heat exchanger with the soil. Investigations are currently being made to describe the process: time constant, temperature range, etc.

A finite difference model for heat conduction and convection is being used for estimating the amount of energy which may be recovered from the ground through the steel walls of the storage tanks under different operating conditions. The results of this study are soon to be published.

4.4 *Heat pumps*

The heat pumps were kept in use for the length of the heating season. Monitoring proved that the system performance was quite satisfactory as far as thermal indicators are concerned. Table 4 shows performance indicators on a monthly basis on the whole heating period for the heat pump connected to the water tanks. It is seen that the performances drop significantly when the electrical energy needed to move water through the heat pump is included in the energy balance. C.O.P. values agree relatively well with the manufacturer data, although remaining at about 10% lower.

Worse performances are observed in the winter period from January until March, when the temperature difference between condenser and evaporator is at its maximum. Also during this period, the two parallel units of the heat pump were mainly used together; it seems, however, that the separate performances of the two units are a little bit better than that of the whole. We have measured instantaneous C.O.P. values down to 2.5 (including circulating pumps) during January 1985. Generally, good C.O.P. values can be attributed to a correct sizing of exchangers and to the presence of bypass circuits at both cold and warm sides of the heat pump, ensuring at least the 9/5°C (evaporator) and 47/52°C (condenser) optimum conditions.

For the heat pump connected to the earth exchangers, we lack seasonal indicators for the period concerned due to a malfunction of some temperature probes and also because it was only slightly used for storage. Nevertheless, some estimates made during periods of a few days in winter gave C.O.P. values in the range of 3.9 to 4.4, dropping in the range of 2.4 to 2.8 when the electrical energy of circulating pumps are included in the balance. The power requirement for these pumps amounts to 6 kW (versus 4 kW for the water/water heat pump unit).

4.5 *The system as a whole*

Looking at the system's performance since the summer of 1983, we may give the following average values. Of the 900 GJ required annually, half is given by the electrical backup heating element and the other half is supplied by the heat pumps. The solar fraction, taken as the ratio of the energy supplied for free to the total energy requirement, is 0.3. The water storage effectiveness is 0.7; we have not been able to assess that of the storage in earth.

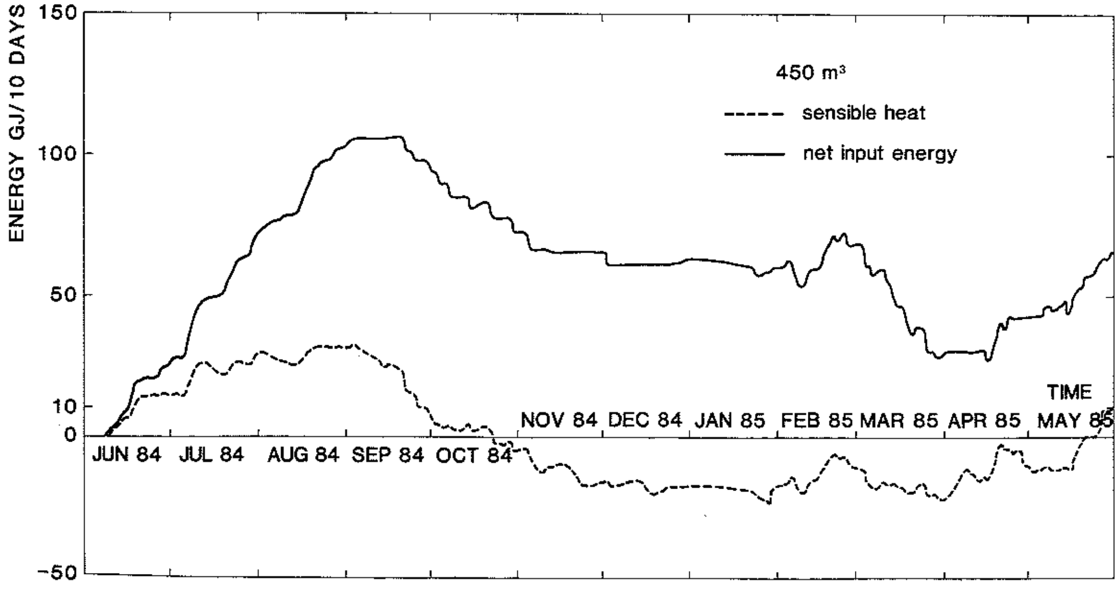

Fig. 5. Net energy input and variation in sensible heat content in the water storage.

Table 4. Measured performance indicators on a monthly basis for the heat pump connected to the water tanks

Month/year	Electrical energy (compressor + pumps) (MJ)	Thermal energy (condenser) (MJ)	Mean temperature at evaporator inlet (°C)	Mean temperature at condenser outlet (°C)	Mean COP including circulating pumps	Mean COP excluding circulating pumps
Sep 1984	5242	22788	18.4	41.9	4.35	4.98
Oct 1984	5483	23580	18.1	42.2	4.30	4.92
Nov 1984	13014	49860	14.7	44.6	3.83	4.37
Dec 1984	2376	8838	12.4	42.2	3.72	4.28
Jan 1984	3294	10152	11.1	48.2	3.08	3.28
Feb 1985	8478	26028	14.7	44.3	3.07	3.34
Mar 1985	19008	57420	12.3	42.7	3.02	3.38
Apr 1985	4536	18612	16.6	40.4	4.10	4.72
May 1985	5220	20880	15.5	35.6	4.00	4.59
Annual values	66651	238158	14.8	42.4	3.57	3.98

5. DISCUSSION

The system at the Fondation Universitaire Luxembourgeoise is a complex one, using solar energy collectors, various energy storage techniques, and a computer for overall control. The data processed has shown that each of these subsystems has apparently performed adequately. The main difficulty is to control the flow between these subsystems efficiently, establishing priorities and a yearly operating strategy. In our experiment, we have taken this problem on by analyzing the system bit by bit: this year, we looked at the buried water tanks; next year, we shall particularly be looking at the heat exchangers buried in earth. Another difficulty is meeting the building's heating requirements, the first priority being to provide comfort in the offices and laboratories, sometimes to the detriment of an interesting experiment. As far as the solar collectors are concerned, the arbitrary 400 W/m^2 insolation threshold could certainly be lowered. Our present idea is to let the threshold vary as a function of climatic conditions and the state of the storage, and to modify the solar collector fluid pumping rate automatically so that its temperature is appropriate for storage.

It is interesting to note that the solar ratio we worked out is higher than the estimated ideal ratio for a single cycle of the system. There are two reasons why the system performed so well. First, for three months, the buried tanks were used for short-term storage (of a few days), thus increasing the number of charge–discharge cycles. Second, the energy "lost" through the bottom of the storage tanks was partially recovered when the temperature in the tanks dropped below the natural ground temperature. The heat pumps high C.O.P.'s are due to automatic bypass systems both at the evaporators and at the condensers, thus ensuring virtually constant temperatures at both exchangers.

6. CONCLUSIONS

We have analyzed the performance of the hybrid interseasonal solar-heating and storage system at the Fondation Universitaire Luxembourgeoise. The first period of measurements has already given interesting results, and at the outcome of two further annual cycles, we expect to reach our conclusions on the choice of interseasonal storage systems and their sizing for this type of use. Nevertheless, we are able to state already some conclusions based on first results. These conclusions could help the future designers of such systems.

For this complex heating plant, the control system is of prime importance and a computer is a necessity. The good performance indicators of the solar collectors are mainly due to a low brine temperature and due to a careful placing. The surface-to-volume ratio is not optimal for the 10 buried tanks: a single large volume of 500 m^3 would be better to reduce heat losses. A lower operating temperature setting for the heat pump evaporator would probably increase the amount of heat available from the heat pumps by recovering energy below the natural ground temperature. Future follow-up of the heating plant will especially focus on the ground heat exchanger and on the energy losses from the water tanks.

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