DESIGN, REALISATION AND EVALUATION OF A PILOT LARGE SCALE SOLAR THERMAL PLANT IN NORTHERN ITALY

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Abstract – The purpose of this article is to describe the realisation of a Large Scale Solar Heating Plant (LSSHP) in Italy, to present the results of its dynamic simulation as well as to introduce a systematic method for the problem of the variable flow optimisation strategy. A 200 m$^2$ solar heating plant is built at Melegnano (Italy) and is currently (April 2000) at the commissioning phase. It is a pilot LSSHP, realised with the scope to introduce successfully this technology in Italy. A simple form of a “Guarantee of Solar Results Contract” is applied and a list of maintenance rules is created. A detailed monitoring configuration is implemented and a flexible control unit is chosen and programmed. According to the results of the detailed simulation of the plant (done by TRNSYS) the energy gains are 630 kWh/m$^2$ per year. The plant will cover around 80% of the DHW load and will deliver approximately 33 MWh to the swimming pools water at an annual basis. A theoretical procedure is created for the optimisation of the variable flow rate of the LSSHPs and is to be applied and validated in the case of Melegnano. It is based on the Hooke and Jeeves direct search optimisation method. The effects of the load pattern on the optimum flow rate profile are examined. The first results have illustrated a theoretical increase of the plant performance by 2% in some cases.

1. INTRODUCTION

The Italian solar thermal market is week if compared with those of other European countries. The solar sales per year amount to a few tens of thousand m$^2$, while in some other European countries (like Austria and Germany) this number rises to some hundreds of thousand m$^2$. The situation is even worse in what concerns the Large Scale Solar Heating Plants (LSSHP). Until 1999, forty-six (46) plants with more than 500 m$^2$ were currently in operation in Europe, but none in Italy.

A collaboration of the Technical University (“Politecnico”) of Milan, Engineering Department, with the Municipality of Melegnano (situated in the Province of Milan) has permitted the construction of a pilot LSSHP in Italy. The plant of Melegnano is realised in the ambit of the European Project THERMIE A – REB/0061/97: “LSSH systems for housing developments”.

A team of professionals, in collaboration with the group of “Environmental Physics – Energy Department” of Milan “Politecnico” has carried out the design and supervision of Melegnano’s project. The solar plant has been designed with the aim of covering a substantial part of the DHW load and use the excess of solar gains to partially heat the swimming pool (SP) water. In Melegnano, two swimming pools exist: an uncovered one for the hot season and a covered pool for the winter. Thus, the SP centre is in operation throughout the whole year. The coupling of the plant with the SPs allowed the size of the collectors field to be larger than for a normal DHW plant, without scarifying in economical performance.

The design of the plant has been based on selected information offered by the LSSHPs evaluation reports (as, for example, that of [Dalenbäck, 1997]), as well as on personal communications with experts.

Melegnano’s solar plant has three main objectives:
1. To introduce and disseminate the LSSHPs technology in Italy;
2. To create the guidelines for the realisation of a larger solar system in the residential area nearby the actual plant;
3. To analyse various control strategies and examine the aspect of variable flow (VF) optimisation in depth.

2. PLANT DESCRIPTION

2.1 Main components configuration

The 200 m$^2$ of flat plate collectors are positioned on the roof of the winter SP building and are due south at an inclination of 45°. The largest collectors (12.5 m$^2$ each) available on the market and used for the LSSHPs constructions have been chosen. Sixteen collectors have been mounted; they form two rows connected in parallel, each row having eight collectors connected in series. As in almost all the LSSHPs, the low flow principle has been adopted. The nominal flow is 10 kg/(m$^2$·h).

However, each one of the solar plant pumps is driven by an inverter and, thus, VF profiles are possible. The VF range to be adopted is from 6 to 20 kg/(m$^2$·h).

The plant configuration has been as simple as possible; it is illustrated in a simplified way in figure 1.

In the primary solar circuit the two heat exchangers have been connected in series in order to avoid a complicated hydraulic configuration. Due to the limitations of the technical room, the storage has been divided into two tanks of 5 m$^3$ each, connected in series. The storage vessels are made of steel with a special internal glass-type treatment applied and a 10 cm of mineral wool insulation. The auxiliary heating system (natural gas boiler) is affecting a part of Tank 1.
The water versus the collectors heat exchanger is always drawn from the lower possible level of tank 2. At about the same level, the water refill from the mains is entering. After the water has been heated at the collectors heat exchanger, a diverting valve will direct it towards the top of tank 1 or 2, depending on its temperature. The two tanks connected in series are practically equivalent to a single tank of double volume (let us imagine tank 1 positioned on the top of tank 2), with the hot water entering at either the top or the middle of this double tank. The connection tube allows flow in both directions.

Counter-flow, plate heat exchangers are used. At nominal operating conditions (irradiance of 800 W/m² and flow rate of 10 kg/(m²·h)), their logarithmic mean temperature difference is near 5 K.

2.2 Freezing and overheat protections

The primary circuit has been filled with a mixture of water and glycol (33% by volume), thus being able to stand temperatures as low as −17 °C.

On the other hand, there are no overheating risks for the plant since its dimensioning permits the delivery of any excess heat to the swimming pools. Anywise, the expansion vessels available volume (400 litres in total) makes the plant able to stand stagnation.

2.3 Control equipment

The solar plant of Melegnano presents some peculiarities that affected the choice of its control system. These are mainly the VF optimisation procedure to be carried out, the high number of sensors installed and the remote control and (tele)monitoring requirements. The requested features of the control system are listed bellow:

- Freely programmable, having the possibility of advanced parameters elaboration.
- Easily expandable to allow, eventually, additional input or output signals.
- Possibility to be completely by-passed from a computer.

Moreover, the control system applied consents the use of some alarm phone call messages. A preliminary list of the situations that may create an alarm message is following.

- Too high temperatures in the tank(s) T>95°C.
- Stagnation conditions for the collectors circuit.
- Too high pressure at the collectors primary circuit (near to the security valve settings: 6.5 bars).
- Temperature of less than 45° at the top of tank 1.
- Alarm signal from a pump’s state of operation.
- Sanitary water consumption at night-time (leakage).
- Measurements outside the expected range (malfunctioning of sensors).
- High discrepancy between the expected and the measured values of Np (the number of functioning hours of the solar primary circuit pump) or of the collector gains (Qcoll).

Practically, the control unit combined with a PC and the connection with the telephone line has assumed the additional features of (tele)monitoring and remote control. By means of this control unit, all measurements are done (even those not related with the control strategy) and all equipment can be controlled in a manner that may be changed at any time by using the appropriate software tool and re-programming the unit.

The following list illustrates the various steps of the control strategy procedure:

- At the beginning of the plant operation (while writing this article) a basic fixed flow (FF) rate strategy is implemented. It is dependent on only few plant sensors and based in common engineering practice adopted at medium-large scale solar plants.
- A period of at least one month of data acquisition and elaboration will permit the dynamic test of the plant and the validation of the TRNSYS simulation model.
- Once a validated model has been achieved, a procedure of control strategy optimisation will follow, focused on the VF rate aspect.
- At the end of the first year of operation, the best strategy will be chosen. The criteria of the choice will be based on the corresponding energy performance of the plant as well as on the cost effectiveness and simplicity of its implementation and utilisation in other, similar, plants.

3. REMOTE CONTROL AND MONITORING

3.1 Monitoring configuration

A detailed monitoring equipment configuration was designed for the plant of Melegnano to enable the accurate evaluation of the system performance at various conditions. The European financing has permitted the use of high accuracy equipment. For the energy measurements, it has been decided to use always flow meters and temperature sensors independent to each other and calculate the energy flows, instead of compact “energy meters” that could offer less accuracy. The planning of the monitoring configuration and the design of the plant occurred simultaneously, to ensure compatibility and facilitate the installation of the equipment. The measuring devices are connected to the main control unit and, consequently, to the PC located at the technical room where one minute mean values are transmitted and stored. Only some of the monitoring equipment devices are necessary for the plant operation and will remain in the plant even after the end of the monitoring period. The exact number and position of the measuring devices that will remain on the plant is still to be defined and depends on the complexity of the final control strategy that will be implemented.

The monitoring equipment for the whole plant is listed below:

- 12 temperature sensors (PT100, 3-wires) of 300mm length each for the measuring of the temperature in various levels of the storage vessels.
- 14 temperature sensors (PT100, 3-wires) of 50mm length each for the measuring of the temperature in various points of the piping circuits.
- 2 sensors for the measuring of the ambient temperature: one for the external temperature (mounted on the level of the collectors field) and one for the temperature in the technical room.
- 5 flow meters for the following circuits: primary of collectors, secondary of DHW tanks, swimming pool, secondary of auxiliary and recirculation.
- 1 pressure meter for the primary collectors circuit.
- 1 pyranometer at collectors inclination.
- 1 anemometer at the collectors field.

Figure 2 is a schematic representation of the collectors and heat exchangers circuit monitoring configuration. Standard equipment (for visual inspection only) is represented by dotted

1 A contract has been signed between the Municipality of Melegnano and the Politecnico of Milan; the later will carry the remote control and telemonitoring of the plant for one year after the commissioning.
lines in the figure. For the sake of simplicity, only the main components of the plant are illustrated.

Fig. 2: Monitoring equipment on collectors circuit

Legend of fig. 2: \( T_{amb} \): Ambient temperature; \( U_{wind} \): wind speed; \( G_{glob} \): global irradiance at collectors level; \( SC \): solar collectors; \( HE \): heat exchangers; \( TM, FM, PM \) and \( EM \): temperature, flow rate, pressure and energy meters respectively. Conventional equipment is shown in dotted lines.

3.2 Remote control and monitoring

The tele-monitoring and remote control configuration scheme is shown in figure 3.

![Remote control and tele-monitoring layout](image)

Fig. 3: Remote control and tele-monitoring layout

Once the plant commissioning is completed, the local PC (PC 1) will take the control by-passing the Local Control Unit (LCU) in order to facilitate the strategy optimisation procedure. Thus, all output signals that are (in any case) generated by the LCU will depend on the variables that PC 1 is communicating to the LCU.

The PC of the “Politecnico” (PC 2) is connected, whenever desired, to PC 1 by means of modem/phone line. An appropriate software (PC-Anywhere) is used to have full control of PC 1.

The LCU will take the control in two cases:

- When PC 1 is not working properly.
- When an appropriate command is given by PC 1 (or by PC 2 since it has full control of PC 1).

The logic of the LCU may be programmed by PC 1 (or 2) without interrupting the plant operation.

If PC 1 is not working properly and the LCU has the control, the plant can still be monitored and certain remote control features exercised by PC 2. This is possible since the LCU has an internal modem and is connected directly to the telephone line. This feature will ensure, apart from the supervision of the plant operation, that no useful data will be lost. In fact, the LCU has the possibility to restore a limited amount of data. For the purposes of this plant, if only the LCU is saving the data values (i.e. PC 1 is not working) then its memory should be refreshed more or less once a day if the measurements are saved as 5 minutes mean values. Thus, one phone call per day from PC 2 is enough to ensure a complete data acquisition until PC 1 is repaired.

4. SIMULATION RESULTS

The software TRNSYS is used to construct the model for the simulation of Melegnano’s solar plant. The technical characteristics of the plant equipment, as specified by the manufacturers, are used as input data together with the available weather data for the nearest area (Milan). It is not the purpose of this document to present the simulation procedure into details, since it hasn’t been validated yet. The main monthly energy values prediction is illustrated in fig 4.

![Main energy values for Melegnano’s solar plant](image)

Fig. 4: Main energy values for Melegnano’s solar plant

For each month, the first “brick filled” column represents the load of DHW. The second “plain” column, (existing only for the hottest months) is the energy delivered by the solar plant into the swimming pools circuit. The third column (filled by inclined lines) is the total solar gain. As seen, the solar plant gains are covering the whole DHW load for seven months. According to the simulations the total annual solar gains are 630 kWh/m². The solar fraction with respect to the DHW load is 79%. The excess heat during the hottest months is delivered to the swimming pools and is equal to 33 MWh per year.

5. PLANT REALISATION AND MANAGEMENT

5.1 Design and construction

Being public, the plant of Melegnano had to follow a call for tenders procedure. This fact, together with the lack of experienced installers of solar plants in Italy created the necessity of a very detailed design. It was not enough to specify the technical characteristics for each component. All parts of the plant, from the collectors down to the smallest valve or tee piece had to be chosen one by one, specifying the construction company and model. This approach proved to be fruitful; it has eliminated the common tendency to use secondary quality (and cheaper) components at the construction phase.

A know-how transfer agreement has been achieved between the installer and the solar plants construction Company that provided the collectors (SOLID, Austria). The Italian workers have been trained by the experts of SOLID for a quick and correct installation of the collectors. Figure 5 is a photo showing the positioning of a collector on the filed.
A procedure was to be accomplished by an independent and reliable body (Politecnico of Milan). Finally, a high margin has been intentionally applied to the minimum amount of heat to be delivered annually; it is substantially lower if compared with the simulation predictions.

For solar plants facing the risk to meet a lower than expected load, a similar to the above contract may be formulated, with the additional term that its validity should be maintained as far as the annual load exceeds a minimum value. Actually, the situation may be more complicated since the performance of the plant depends not only on the total amount of the annual load but also on its distribution on time. Thus, [Dalenbäck, 1999] suggests that the most reliable term for the “guarantee of solar results” contract is the continuous monitoring of the collectors efficiency curve. According to this principle, if the collectors field has maintained its pre-stabilised efficiency, unfavourable load conditions that have penalised the plant performance will not affect the installer.

To conclude, we believe that the type of contract applied in Melegnano is certainly helpful and has drawn some guidelines, but more work has to be carried out in order to repeat it in other LSSHPs in the future.

5.4 Maintenance rules

The lifetime of solar thermal plants is usually estimated to be 20 years, with some experts sustaining lifetimes up to 25 years. There is a general agreement that the maintenance requirements for the solar plants (especially for the LSSHPs that benefit from the effects of scale) do not represent a substantial amount of the plant annualised cost. Maintenance is a very important issue which influences both the lifetime and the annual performance of the plant. However, there are not well established procedures for the inspection and eventual maintenance that the solar plants should have. In the case of Melegnano, a leaflet of instructions for the inspection and maintenance of the plant is being prepared and will be distributed to the responsible for its operation. The list has been based mainly on the suggestions of experts that have realised many LSSHPs and are currently responsible for their maintenance [Holter, 1999]. Some of the instructions for actions and/or measurements that are not specific for Melegnano’s plant are presented in the following list as guidelines.

Once a month:

- Check of the operating pressures. By checking the stability of the pressure values on the primary collectors circuit it is guaranteed that the system has not loose any glycol mixture because of leakage or by eventual opening of the security valves. Additionally, the pressure drop on the DHW side of the heat exchangers should be controlled. If a substantial increase is observed in time, then it is possible that some deposit procedure is on course and the heat exchanger(s) may need to be cleaned2.

- The total number of hours of the pumps functioning, if possible1.

2 Apart from cleaning the heat exchanger, it may be necessary to install a desalination unit in the sanitary water circuit if the increase of the pressure drop has occurred suddenly. Actually, when there are some indications that such a unit has to be applied, then the decision is based on the heat exchanger pressure drop variation on the first month of the plant’s operation.

Only plants with a sophisticated monitoring system will permit this option. Apart from giving evidence to malfunctioning, it may help at the identification of some correct/optional set points of the plant’s control strategy.
• The energy output of the plant. Once a year:
  • The security valves should be opened for some seconds.
  • If it is not too costly, an apposite chemical analysis may identify the condition of the glycol mixture. Alternatively, a control of the glycol mixture pH may give an indication of its conditions. The lower acceptable limit for the pH is 7. While this method is very simple (it needs only some “litmus paper”) and its cost is negligible, it is not to be considered accurate.

It should be taken into consideration that the anti-corrosion additives of the glycol mixture are destroyed mainly in case the plant is remaining at high stagnation temperatures frequently or for extended periods.

The above mentioned inspections could be effected (with a small additional cost) by the same person(s) who is (are) responsible for the conventional heating plant maintenance.

5.5 Problems encountered

As already mentioned, there is practically no experience in the realisation of LSSHPs in Italy. Additionally, the detailed monitoring requirements and the (double) connections with the swimming pools have complicated the plant configuration. These facts caused serious obstacles and delays in the current realisation. However, the lessons learned from this experience are invaluable for both installers and designers.

Some serious problems occurred with the temperatures monitoring. Inexperience of the designers and misleading information provided from the control unit Company, lead to imprecise temperature measurements. More specifically, instead of a standard 3-wire connection of the PT100 sensors, only 2 wires can be used leading to errors due to the wires resistance. A calibration procedure (and a shifting of the measured values) reduced the imprecision but the results are not satisfying. It now seems that our requirement to combine the control unit with the monitoring procedure was not compatible with the high precision standards required at this specific plant.

5.6 Dissemination

The plant is installed in the public swimming centre of Melegnano. This is a highly frequented centre by all ages and social classes. Thus, the plant position will help the local community to get familiar with solar energy. Moreover, the following dissemination activities are envisioned:

• The Municipality of Melegnano, being an active member of the Italian Municipalities Association (ANCI), will present and promote the benefits from the realisation of this pilot plant at a national level.
• At a local level, the Municipality will disseminate the results to the residents of the town by means of a brochure, some visits and a happening. Moreover, some results during the monitoring will be periodically presented to the swimming pool users.
• Educational and technical visits will be arranged from “Politecnico” of Milan, addressed to schools, University students and teachers, as well as technicians. Many elements of the plant’s realisation and evaluation procedure will be used as teaching material for some courses in the Engineering Department.
• The plant will be presented to “ASSOLTERM” (Italian Solar Thermal Association) as well as to the Italian sector of ISES and further promoted by them.

6. VARIABLE FLOW OPTIMISATION

6.1 Introduction and literature review

The issue of variable flow (VF) optimisation has not been fully analysed. Specifically, there is no accordance between experts whether VF may increase the system performance and how, or it may only have advantages of practical nature. Some of them sustain that VF may only permit a better control of the auxiliary heating working time, avoiding, for example, too frequent on and off turnings. Others believe that, by using VF, the energy yield of the system may increase.

An evidence that the VF question has not been fully addressed is the recent evaluation of Marstal Central Solar Heating Plant [Heller et al., 1999]. Using a validated simulation model, Heller et al. have shown that the VF strategy adopted in Marstal not only was not optimum but it was worse (by 2.7% in terms of annual energy gains) than an optimised fixed flow (FF) strategy.

While there exist some references addressed to the FF optimisation problem, there are little that examine the VF. For what concerns the FF optimisation problem, two were the common results expressed in the related literature:

• Low flow rates (around 10 kg/(m²*h)) are advantageous in terms of the solar system gains, compared with the “conventional” high flow rates (around 50 kg/(m²*h)).
• The optimum FF rate for a solar plant with daily storage was found always near to the so called “Single Pass”. This means that the water content of the tank was circulated trough the collectors (or the collectors heat exchanger) only once and no turnover occurred.

Some attempts have been made by [Wuestling et al., 1985] to apply a VF strategy. The flow variation in order to achieve a constant temperature collectors output throughout the whole year led to lower plant performance respect to the optimised FF rate. The best method found by Wuestling et al. was to vary the flow proportionally to the utilisable radiation, i.e. to the difference between the radiation incident to the collector and the critical threshold radiation level. However, even with this method the results were just equal to the optimum FF performance.

The latest work on this aspect is done by [Al-Ibrahim et al., 1998] and regards an optimisation search for a photovoltaic (PV) driven solar heating plant. The goal is to find, among the possible PV pumping systems’ flow rate profiles, the profile that maximises the performance of a given solar DHW system. It resulted that if the flow rate is proportional to the square root of the utilisable radiation, the performance of the system is increasing, although the value of the improvement is not mentioned. However, in this case the square root function was imposed by the physical characteristics of the PV-pump.

8 The application of, at least, one energy meter (for example at the level of the primary side of the collectors circuit) is suggested for the correct inspection of the plant’s operation. On the other hand, in cases where the “garantee of solar results” is applied or when the owner is selling solar thermal energy, the energy delivery measurement is necessary. Its cost is usually negligible for a large scale solar heating plant. A monthly inspection of some main energy value(s) may easily give evidence to some malfunctioning, especially if the incident solar radiation is measured as well.
9 The reason is the following: if a security valve has never functioned for a long period then its opening pressure limit may increase with time.
coupling problem. Thus, the aim was not to find an unconstraint optimum VF profile but was highly plant specific. Nowadays, the use of VF in medium-large solar plants is rapidly increasing since the pumps models with an incorporated inverter are commonly used and do not present high additional costs.

6.2 VF optimisation method and results.
There are some prerequisites that have to be respected in order to understand the physical rules that govern the VF optimisation problem. The basic requirement is that the gains of the solar plant to be examined should never exceed the load. If, as happens frequently, the solar plant covers 100% of the load during summer, then there is no mean to search for a better performance during this period.

Another need is to work on a simple plant, and obtain relatively short simulation run times since a large number of runs has to be made.

Due to the above reasons, the model used for the simulation of Melegnano’s plant was not appropriate for this first approach. A simpler and smaller “direct” (i.e. without heat exchangers) plant of 80m² with one storage vessel has been chosen. The load was similar to the one in Melegnano, but it was never covered to a 100% by the solar gains.

The mathematical problem of flow optimisation in a solar plant with VF is not trivial. Its complexity has excluded the search of an analytical solution. Consequently, a so called “direct search method” had to be used. The only requirement of the direct search methods is that the function to be maximised (or minimised) has to be continuous.

The method chosen is that of Hooke and Jeeves [Walsh, 1975] (or minimised) has to be continuous. To avoid the effect of initial conditions, a sequence of ten days is created, all being identical to the single day under exam.

The daily flow rate profile is defined as a vector having as arguments the flow rate values at different time segments of the day. The period of pumps operation is divided in 9 segments, allowing a (variable) value for each segment extreme. The thermal equivalent of the parasitic pumps electric consumption has been subtracted from the solar gains.

For each flow profile trial, a TRNSYS simulation is executed providing the resulting solar energy gains to the algorithm. Thus, the algorithm generates a new profile by the so called “exploration” and “advancing” moves (see [Walsh, 1975] for a thorough description of the algorithm) until it finds the profile that results in maximum solar energy gains.

The weather data available for Milan (Italy) are used in this study. A hypothetical “flat” DHW consumption profile, occurring from 6:00 to 18:00 has been assumed. The main aspect to be examined is the effect of the day’s main characteristics (profile of radiation and temperature) on the optimised VF profile. Figure 6 shows the resulting profiles for three different days of the year: a sunny summer day (day 172 of the year), a sunny spring day (day 120) and a half - cloudy spring day (day 102).

As seen in the figure, the sunny days profiles are similar but the one of day 102 is quite different. This excluded the research of a mathematical expression, common for all days of the year, that relates the solar irradiance with the instantaneous flow rate. The energy gains for each day group is presented in table 1.

![Fig. 6: Comparison of VF profiles for days 172, 120, 102](image)

As seen in the table, the highest increase in performance occurs for the summer sunny day and amounts to 2.4%. It has to be considered that the performance’s increase is calculated with respect to the optimum FF rate for each specific day. In a real plant without VF possibilities, the FF can be optimised for the whole year only; thus the real improvement of the VF profile may be higher than that presented in the table.

On the other hand, it has to be noticed that for the identification of the optimum VF the knowledge of the climatic conditions in advance has been assumed. This is not the case in reality, where only the weather forecast is available.

Additionally, the effect of the DHW consumption profile on the VF optimisation has been examined. Although it is not possible to present here the results in detail, it is worth saying that a strong dependence exist and that the more the DHW profile occurs during “sunny” hours, the higher the advantages of the VF strategy may result.

6.3 Further discussion on the optimisation methodology
Although the Hooke and Jeeves method has been successful in the search of the optimum VF profile, the computational effort is still high. Meantly, three quarters of an hour (about 180 TRNSYS simulations) are needed to find the optimum flow profile for every single day when the program is running on a Pentium-II 300 MHz PC with 128 MB of RAM memory. This large duration has excluded any attempt to search the optimum VF profile with a higher resolution in time than the 9 segments applied. The above comments lead to the consideration that a quicker algorithm should be applied. The method of Nedler and Mead [Walsh, 1975], known also as a Simplex Method, seems to be a possible alternative.
Another problem is that the method may lead to a local and not global maximum. Up to now, the following procedure is used in order to overcome this problem.

- For the first vector initialisation the optimum FF profile of the day is found and used.
- Secondly, the extreme flow rate values are also tested as initial conditions.
- Thirdly, an optimised VF profile of another similar day is applied to start the search.
- The best result is selected and the algorithm step length is modified to check if an even better result can be achieved. These empirical trials have been successful and lead to consistent results for all the days examined.

A systematic approach for a “smart” initialisation of the flow rates vector should be applied to permit an evolution of the method, so that the whole year optimum VF rate profile can be determined accurately and an exact number for the maximum achievable performance increase calculated.

An empirical sensitivity analysis has shown that the results of plant performance increase achieved are practically independent to many design characteristics like the collectors efficiency curve, the storage volume and dimensions, the insulation of storage and pipes etc, when those characteristics respect the common engineering practice of LSSHPs. Results are also independent with respect to many parameters of the simulation models like, for example, the number of nodes and the allowed integration errors of type 140. All the above mentioned parameters have been casually changed to their extreme values (maintaining, as said, a reasonable validity range) and the results were practically unaffected. This shows that the results achieved are not “plant specific” but can be generalised to solar DHW plants of similar dimensions, providing they have similar solar fractions.

Up to now, the resulted flow rate of each time segment defines the strategy to be adopted for an optimised control of the plant. However, in practical terms, other variables should also be used alternatively, if the methodology followed here is to be applied in a real plant. For example, instead of defining the flow, the desired temperature levels for the various nodes) for different initial conditions.

The whole optimisation procedure requires some knowledge of the future weather conditions at least for a day in advance. However, for the case weather forecast is not available or the predictions are wrong, a statistical elaboration of the irradiance and ambient temperature data should be used in order to achieve some alternative general rules for the flow profile to be applied.

Another interesting aspect is linked to the level of the radiation threshold ($G_{th}$) applied. To the extend of the actual analysis, $G_{th}$ has been optimised only once, for the case of FF throughout the year. This is probably a good approximation, but it is certainly interesting to allow $G_{th}$ to be variable and its value to be optimised in the case of VF. Moreover, the values of optimum $G_{th}$ may be different for the start time with respect to the stop time of the pumps operation since there are different temperature conditions ($T_{amb}$ and $T_{tank}$ for the various nodes) for the two cases.

As a final remark, the global daily flow found is near the “Single Pass”; confirming the validity of this principle.

The work is up to now at a theoretical simplified level. The following list represents the main aspects that have to be further investigated:

- Include the heat exchangers in the simulation model to analyse their effect.
- Examine the effects of the weather and load profiles prediction uncertainty.
- Validate the results with practical tests on Melegnano’s plant.

7. CONCLUSIONS

Despite the problems encountered, the whole project can already be considered successful. The plant is currently working at a satisfactory (but not yet optimised) mode and has responded as expected to the first operation tests. The simplified “Guarantee of Solar Results Contract” applied was helpful for the quality of the plant. The first data achieved from monitoring show wide opportunities for optimisation of the plant operation. Its innovative nature in the Italian context as well as its advanced features (telemonitoring, remote control, VF control) are enhancing its potential for the dissemination of the LSSHPs and may contribute to the expansion of the solar thermal market in general. Finally, the first theoretical considerations on the aspect of VF optimisation show some potential performance improvement that will be further examined and tested in practice in Melegnano’s plant.

REFERENCES


