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ADVANCES IN LARGE-SCALE SOLAR HEATING AND LONG-TERM STORAGE IN DENMARK

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Abstract – According to (the) information from the European Large-Scale Solar Heating Network, (See http://www.hvac.chalmers.se/cshp/), the area of installed solar collectors for large-scale application is in Europe, approximately 8 mill m^2, corresponding to about 4000 MW thermal power. The 11 plants of the total 51 plants are equipped with long-term storage. In Denmark, 7 plants are installed, comprising of approx. 18,000-m2 collector area with new plants planned. The development of these plants and the involved technologies will be presented in this paper, with a focus on the improvements for Danish Central Solar Heating Plants, servicing District Heating and related developments in large-scale thermal storage.

Central solar heating today is a mature and economic realistic solution for district heating based on a renewable source. The cost for solar collectors has decreased by nearly ¼ during the last 10 years and the corresponding cost per collector area for the final installed plant is kept constant, even so the solar production is increased.

Unfortunately large-scale seasonal storage was not able to keep up with the advances in solar technology, at least for pit water and gravel storage technologies. There are severe problems with the tightening of pit and lid constructions. First solutions applying thin stainless steel liners are found and demonstrated for pit lining. Similar solutions based on polymer liners are many times cheaper, but seem not reliable at the moment due to material degradation and resulting reduction of the lifetime. The improvements of polymer liners seem realistic and is expected to be solved in the coming years. Floating pit lid designs are in the phase of being tested this year and first results are expected soon.

1. INTRODUCTION

Experiences in Central Solar Heating Plants (CSHP) and Large-Scale thermal storage are to be published in the "Solar Energy" Journal soon by (Heller, A., 2000) . This paper is a follow up to the article in the journal, summing up some of the aspects not covered there. The presentation will take its point of origin, where the European Project, the APAS-project, stopped (Fisch, N., Gigas, M., and Kübler, R., 1996) .

In literature, two types of Central Solar Heating Plants (CSHP) are distiguished between:

1) Block plants, where the solar collectors are mounted on roof tops, servicing a block of buildings in a small distribution net.

2) District Heating plants, where the collector field is placed in large fields on ground, servicing a district heating system.

To avoid confusion the following acronyms are introduced here:

1) Central Solar Block Heating Plants (CSBHP)

2) Central Solar District Heating Plants (CSDHP).

Combining these acronyms with the ones introduced in the APAS-project to distinguish between thermal storage types applied in CSHPs, leads to a better identification of plant types. Storage asynchronies are

xS : No storage is applied

DS : Diurnal Storage

SS : long-term storage or Seasonal Storage.

First attempts to design "large-scale" solar heating were made in the late 70s in Denmark. Here a number of different renewables were mixed to a rather confuse solution where solar were producing 2% of the total energy demand. This attempt never let to any applicable systems. Later attempts were focused on the solar parts. The main two system designs will be presented in this paper.

2. LARGE-SCALE SOLAR HEATING

2.1. The first attempts

In the late 80s, Danish consultants where transferring the experiences made at Swedish large-scale solar heating for district heating to Denmark. This knowledge transfer resulted in, among other things, the HT-SCANCON collector design by ARCON Solvarme A/S, a 12 m^2 plane module, consisting of a selective strips absorber and one Teflon and one glass cover. The two first central solar heating plants were built in Saltum and Ry, in 1988 and 1989 respectively.

This first generation plants are designed as follows: The HT collectors are placed in rows of 10 modules and the rows are connected parallel to blocks. The pumps of the collector loop (primary side) are running when the solar radiation exceeds 100 W m^{-2}, by an on-off control strategy. The heat is withdrawn through a heat exchanger to the district heating net. The solar heat is feet to the return, cold pipe of the DH system, preheating the fluid in the DH-system. A post-heating backup is necessary, also in summertime. No storage is included. Hence the plant type can be classified as the CSHPxS.

2.2. The second attempt

No appreciable changes were made to the overall plant designs, until 1996, where the Marstal plant was built – here called the second-generation plant. The operators of the plant asked for a design that could deliver constant temperature to the supply pipe of DH-net. To meet the demand, and based on experiences from the district heating technology, variable flow in the solar and the storage loops was adopted. This basic design concept led to a rather complex control strategy. The goal of this strategy was/is, to control the mass flow in a way that the fluid temperature out of the field is at a fixed, high temperature. In summer this temperature is at 80 ^{o}C, where no post-heating is necessary for a long period[1]. This characteristics, together with the employment of a diurnal storage (hence CSHPDS), makes it possible to run the DH-system with a minimum number of staff, a detail that is very important for plant operators and hereby for the dissemination of CSHPs. Experiences from the plant have been reported (Heller, A. and Furbo, S., 1997) and latest results will be shown at the conference by others.

2.3. Comparison of plants and operations

The two plant generations (or types CSHPxS, CSHPDS) have different production characteristics due to the following reasons: a) the absence or employment of heat storage, b) the connection to the DH-system on either the supply or the return pipe, and c) the different control strategies.

A comparison between the two plant designs would be misleading due to these differences. One can conclude from such comparisons, however, that both designs are working well and that both designs are relevant. They offer different characteristics, which gives options for possible investors to chose between.

(Heller, A. and Dahm, J., 1999) presented a study on flow control strategies in the collector loop, for the second-generation plant design. Here a computer model in the simulation environment TRNSYS is applied for the estimation of the thermal yield of the plants. The weak part of such simulations is based on the fact that the load profile - the demand by DH users - varies greatly for different DH systems depending on connected user types and user behavior. The current conclusions are based on a load profile from Marstal, a system with mainly single-family building stock. The main results of the comparison are presented in the following figures, where four control strategies are compared:

- "Marstal original", the strategy applied at the CSHP in Marstal, employing variable flow to obtain return temperature from the collector field of 80 ^{o}C in summertime and 50 ^{o}C in wintertime.
- "Summer operation" where the control settings for summer conditions of the Marstal plant are applied throughout the year.
- "Winter operation" where the control settings for summer conditions of the Marstal plant are applied throughout the year.
- "Constant flow, simple control", where the first generation plant control strategy is applied. Here on-off leads to constant flow pattern.

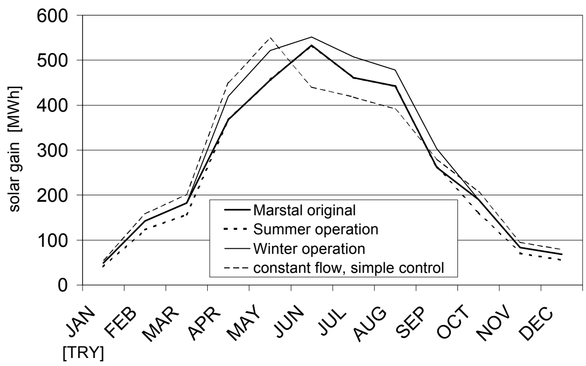

Figure 1. Comparison of the monthly solar gain for different control strategies and the second generation plant (Marstal case).

It is apparent from Figure 1 that constant flow leads to higher solar gain in spring compared to all variable flow control strategies. This can be explained by a rather high heating demand with rather good cooling in the DH-system leading to low forward temperatures to the solar loop and therefore high production. It is also visible from Figure 1 that the "Winter" control lies close to the "constant flow"-production due to the fact that the demanded temperature from the field is so low that the variable flow is close to a constant flow. We find also that the "Marstal original" leads to poorer solar gain for the spring month.

This works in the opposite manner during the summer period, where the main solar production is gained. Here the Marstal-control strategy is superior to a constant flow control strategy. This can mostly be explained by two reasons: a) The absence of heat losses in the auxiliary heaters. b) The greater utilization of storage capacity by high return temperature from the collector field, and also through less mixing. (Note: The Marstal 2100 m^3 water tank storage is equipped with two inlet arrangements, one in the top and one in the middle of the tank). For the constant

[1] This was at least the design criterion.

flow case, a large amount "lukewarm" water is stored in the tank.

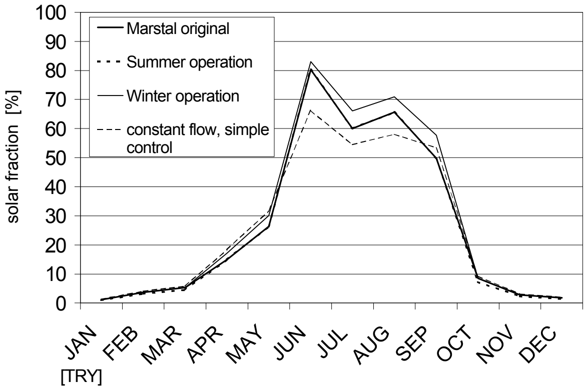

Figure 2. Comparison of the monthly solar fraction for different control strategies and the second generation plant (Marstal case).

Corresponding solar fractions are presented in Figure 2. Here we can see that the Marstal control strategy is superior to the constant control strategy during the whole summer period. Results also indicate that the Marstal variable control strategy can lead to an even better result by control of the demanded return temperature. Two enhancements can be suggested: 1) The demanded return temperature should be made dependent on the tank temperatures. 2) The choice of flow pattern should be made dependent on the efficiency of the collector loop.

The later suggestion is simulated in the mentioned computer model and shows a relevant enhancement in solar gain and solar fraction.

We can therefore conclude that enhancements of the control strategies can be made.

2.4. Economical considerations on CSHPs

The lowest investment is certainly obtained by a collector field with no complex control strategy and no storage involved - the first-generation plant. The investment can be estimated to approximately 65-75% of the Marstal design. This design has a limit due to the fact that the solar heating must be matched by the demand. Cooling is not possible by other means. Hence the solar fraction is limited to between 5 and 8% under Danish conditions, whereas the solar fraction for the second-generation plant lies between 12 and 25%. The total yearly production for the first generation plants is measured to nearly half of the Marstal production. The savings in pumping energy, which accounts for approximately 75% compared to constant flow control, are not included here. Based on these very simple considerations, the cost-benefit ratio for the two plant designs is close to similar with a tendency of better payback time for the second-generation plant. Hence, the choice of plant design is not motivated by payback time considerations, but by total investments and operational reasons.

The collector cost for the Marstal plant is 160 Euro m^{-2}, which is 20% below the lowest price, found in the APAS-project. The total installation cost per square meter solar collector is kept closely constant at approximately 370 Euro m^{-2} (2,700 DKr. m^{-2}) collector area is kept from the first to the second generation plants, even so a storage capacity and complex control strategy is adopted in the later plant design. The resulting energy price is, due to savings in collector production cost and installation costs in the latest 10 years, dropped from 80 Euro MWh^{-1} for the Ry-plant to 60 Euro MWh^{-1} at the Marstal plant.

2.5. General conclusions on CSHPs

From the plant performance monitored during the recent years, the following conclusions can be made:

All plants are working well with very little maintenance necessary. Experienced designers and consultants can install the technology as “standardware”. The challenge is simply to match the heating demand with a proper solar plant size. A number of tools are available for this purpose, spreading from complex computer program, (Klein, S. A. and others, 1996) to very simple sketch tools for introductory assessments (Leenaerts, C, 1997) . Others tools are under development.

From the Marstal plant we find that the size of a single collector block can be 5000 m^2 with no thermal or hydrodynamic instabilities by simple adjustment of pressure valves right after the plant construction.

The monitored solar gain from the Marstal plant during the last three years leads to the conclusion that the plant must be larger if the demand must be met during the three-summer month. Hence an upcoming plant should be designed to at least 18-25% solar fraction by applying either larger storage volume or by increasing the collector area to annual load ratio from the 0.3 m^2 per MWh. At the Marstal plant the storage volume to collector area ratio was designed to 260 m^3 m^{-2} collector area, which made it necessary to perform night cooling by running the solar collector loops backwards, cooling through the solar collectors. This procedure has proved to work very well and leads to new design guidelines. Overheating is no design boundary anymore, night cooling is applied instead, saving storage investments. The collector area to annual load ratio for the plants examined in the APAS-project were 0.1-0.2 m^2 MWh^{-1}, as we find a ratio of 0.3 in Marstal. In the APAS-project it was expected, that the annual output would decrease due to the high ratio value. This is not the case in Marstal were the net output to the DH is higher than found for the relevant plants examined in the APAS-project.

All these comparisons and experiences indicate, that the development in CSHP is still ongoing, leading to better performance and hereby lower cost-benefit ratio of approx. 0.88 for the whole investment, 0.48 for a minimal second-generation plant and 0.38 if the collectors only are considered.

2.6. The future of Collector Developments

In the APAS-project, industrial production and reflector technologies, placed between the solar collector rows are mentioned as the two main sources for improvement in CSHPs.

Production of collectors has been improved, but an industrial production would, according to ARCON Solvarme A/S, demand an annual installation of 5000 m^2 per production line. This would enable the line to be run constantly leading to a price reduction for collectors of 1/3 with no change of technology yet. Based on this consideration and the fact that the potential for the technology in a few relevant European countries is, according to the APAS-project (Zinko, H., Bjärklev, J., and Margen, P., 1996) and (Fisch, N., Gigas, M., and Dalenbäck, J-O., 1998) , estimated to 2 mill. m^2 per year, such a production line is realistic, if the European Communities are meeting their own claims.

Reflectors are no longer installed in any plant since the late 80's. Hence the technology seems not relevant at this point.

The HT-collector applied at most CSHPs suffers from low efficiency at high temperatures due to increasing heat losses, here called Decreasing Efficiency at High Temperatures Collectors (DEHT). To solve this weakness, an anti-reflective cover is mounted on the HT-collectors in Kungälv, Sweden. The collector price is hereby risen, but is expected to be counterbalanced by the increased solar gain. First results are expected to be presented at the conference by Dr. Jan-Olof Dalenbäck, Chalmers University of Technology, Gothenburg, Sweden. The anti-reflective cover approach is one of the developments that are based on the improvements of glass- and window technologies, tacking place in the resent years. Other approaches will be based on improvements in material technologies in general, such as new coating technology for absorber and covers, new insulation materials and so on.

Another approach of solving the heat loss at high temperature is, to apply alternative collector designs. No comprehensive noun is known to characterize this type of collectors. Hence the collectors will here, in direct opposition to the DEHT-collectors, be called HEHT-collectors. Examples of such collectors can be found among tubular vacuum pipe collectors, concentrating collector designs and trough-collectors. A paper on the application of Trough-collectors will be presented by Krüger D., and others at the conference. Similar papers will follow, applying other high-efficiency collectors in CSHPs.

The drawback for the application of HEHT-collectors lies in the relatively high cost. Hence a third approach is to lower the production cost for the collector field. Such an approach is ongoing in Sweden, where a simple concentrating collector design is under development under the name "MaReCo". This collector applied solar concentration collected in simple strip-absorbers instead of relatively high-cost vacuum-pipe absorbers. Papers on these issues will also be presented at the conference.

2.7 The future of plant developments

The development of CSHP, in Denmark, is to demonstrate higher solar fractions and therefore proving the reliability of the technology. Currently, a plant with solar fractions of approximately 20% is installed in Aeroeskoeping, near Marstal. Monitoring is ongoing and first results are expected this year. Another plant, with solar fraction of 50%, is planned in a third village on the island of Aeroe, Store Rise, employing a large-scale thermal storage.

Reduction of plant cost can be achieved by cost reduction for piping, especially the piping underground.

Increasing solar fraction cannot be achieved without increasing storage capacity. Hence the development of large-scale thermal storage is relevant to the dissemination of CSHPs.

3. THE HEAT STORAGE

The development of long-term or seasonal storage is in Denmark, due to historical reasons, closely related to the development of central solar heating. A large share of solar in a DH-system demands large storage volumes. The development of long-term or seasonal storage is rather complex and involves a number of different technologies, spreading from simple water pits to rather complex high temperature, chemical storage systems.

The improvements of underground thermal energy storage (UTES) are not the subject of this presentation, but will be described by others.

In Denmark the work is concentrated on simple, low-price solutions. Hence pit water storage and gravel-pit storage were focused on in the later years. Non is developed to a final stage but partial solutions are under development to be demonstrated in large-scale in the coming year/s.

3.1. Pit Water Storage

In Germany water storage are built as static construction, typically by concrete tanks, tightened by steel-liners (Fisch, N., Gigas, M., and Dalenbäck, J-O., 1998) . Due to the rather expensive solutions, the activities in Denmark are concentrated to less costly solutions. A 4-year program for the development of seasonal storage was started in 1997 and will be evaluated in

the current year. The main findings of the program are presented here:
The first pit water storage was built at the campus of the Technical University of Denmark in 1990 and rearranged to a gravel pit, three years later.
Based on, among others, the experiences from the DTU-pit, a 3,000 m^3 water storage was built at the central solar heating plant in Herlev (Tubberupvænge) in 1991. The storage was made by driving steel sheet piles into the earth, digging the inside material out, insulating the pit with Polyurethan-plates and tightening the pit with an EPDM rubber membrane. (Pedersen, V. P., 1997)
In 1995 the Ottrupgaard pit water storage was built, a 1,500 m^3 store (Wesenberg, C., 1994) , designed with floating lid and hybrid liner of clay and polymer sheet for lining the pit. The liner design was presented by (Duer, K. and Svendsen, S., 1993) and experiences from the design presented by the author (Heller, A., 1997) .
For all the pits, leakage was severe. Concrete element designs were leaking due to material expansion and resulted in crack damages. The pile-sheet solution in Herlev was leaking due to the collapse of the lining and insulation materials, and the Ottrupgaard pit was leaking due to a number of reasons, mistakes at construction stage, in drain design and problems with clay compression.
Except for the clay layer solution, the tightening problem for pit stores is in general solved by the employment of either steel sheet solutions or polymer sheet solutions. A solution, based on steel liners, is found for the Tubberupvaenge store reported in a Danish publication by (Wesenberg, C., 1998) . Here a stainless and acid-proof liner of 0.5 mm is applied. Complete procedures for construction and control are developed. The solution is estimated to 80 Euro m^{-3} storage volume whereas the material cost is approximately 15 Euro m^{-3}. A polymer solution based on Polypropylene liners is applied at the gravel store in Marstal, not published yet. This liner solutions is estimated to 3 Euro m^{-3} store volume (Jensen, N. A., Holm, L., Porsvig, M., Clausen, J. B., Heller, A., Ulbjerg, F., Tambjerg, L., Münster, E., and Sørensen, P. A., 1999) . The weak point for polymer solutions is certainly the lifetime of the material under these rather hard thermo-physical conditions. A research project, published in Danish by (Pedersen, S. and Nielsen, U., 1999) showed severe damage to the material leading to an estimated life-time of 5-6 years for a material with estimated life-time of 20 years given standard test procedures. The difference in life-time estimation is based on the fact that the procedures applied by Pedersen exposes the polymer liner with water on the one and air on the other side of the polymer probe, as the standard procedures involve water-water or air-air interfaces. Given the water-air interface, the additives in the polymer are diffused into the water or degraded by the water interface, leaving the polymer material exposed to physical effects, oldering due to oxidation, the material, supposedly from the airside. Hence additive composition for polymer liners is the key to the problem solving.
Parallel to the liner problem, solutions for the lid design are under investigation. After two years of design projects two lid designs are proposed, (Duer, K., 2000) . Similar to the pit liner solutions, lid design is based on steel-liner or polymer liners. Both solutions can be constructed as static or floating designs. The floating lid is superior economically by a factor 0.7 compared to a minimal static solution.
It is expected that final solutions based on thin steel liner and with a lifetime of 20 years, will be demonstrated in this year and that the price will lie near 40 Euro m^{-3} installed pit. Polymer liner solutions would reduce the price by 1/3 but the lifetime of the liners is rather doubtful. First prototypes will be tested this summer at the rehabilitated DTU-pit.

3.2. Gravel Storage

Gravel storage is demonstrated in Holland and Germany. A pilot store was built at the Marstal CSHP in 1999. A pit was dug and lined by a Polypropylen membrane. The membrane was welded on site to a large sheet. The pit was than filled with layers of gravel and sand. In the sand layers PEX-pipes were installed and connected to a control shaft, placed central in the pit. The heat exchanger length (length of the piping) was found by TRNSYS-calculations based on the ICEPIT-model (Hornberger, M., 1994) .
Results from design and monitoring of the Marstal gravel storage will be presented at the conference by others. The relevant points here are the facts: this storage type cannot compete with pit water storage by neither price nor the thermal performance. The maximum temperature is reduced by the thermal inertia of the construction, dominated by the slow heat conduction in the storage medium. Experiments were carried out at DTU where pipes were placed into different sand materials. Temperatures were measured in pipe and surrounding material. By this experiment, maximum heat transfer rates of 180 W m^{-1} pipe were found for at cold storage and an inlet temperature 40 ^oC above the storage temperature. The draw-off is even more inert. Here 70 W m^{-1} were measured. No convective heat transport was found in the sand material under these experiments (Maureschat, G. and Heller, A., 1997) . On the other hand, gravel storage is a static construction and can therefore be applied in locations with secondary usage of the ground.

3.3. The future

No overall planes are defined for the future of large-scale solar heating in Denmark. The four-year plane must be finalized and evaluated to generate at starting point for further developments. At the moment the future seems to be a straightforward track in the same direction as chosen the last years, a fact that supports a positive evaluation of the last program period.

4. CONCLUSIONS

4.1. CSHPs

Ten years ago, the first central solar heating systems and large-scale thermal storage were built. At the time when the APAS-project was finalized, the success of the developments in CSHP seemed not visual yet. Seen from this time scale, the improvements over the last decade draw a rather successful history for the solar part. Today, CSHPs can be installed with no uncertainties, as a kind of shelf article. Depending on the expected performance, different designs and operations are available. In the future, the cost-benefit conditions for CSHP can and should be improved. This is possible by a number of improvements and approaches as presented in the paper.

At the Marstal CSHP, night cooling is demonstrated with success. Hence new designs must not anymore be driven by the fact that the collector loop must not be boiling. A consequence therefore is, that the tank volume is not to be chosen to avoid boiling. 300 liter per collector area seems a reasonable minimal storage capacity. Such plants can be installed for approximately 370 Euro m^{-2} collector area leading to energy prices of around 60 Euro MWh^{-1}.

4.2. Large-Scale Thermal Storage

The history of large-scale storage shows a series of unfortunate examples with damaged and leaking storage. The very simple task of keeping hot water together with no water leak and low heat losses showed up to be a rather demanding task. Hence the rapidity of storage development cannot keep speed with the development of CSHP in general. This leads to a tendency to apply known technology for the storage part, the application of rather expensive steel-tank solutions. The low-price solutions must be brought forward in it's own speed.

Final solutions to seasonal storage are found for under ground thermal storage, but are still missing for cheep pit storage. The two problems that are to be solved for pit storage are the lid solution and the pit liner solution. As the lid designs seem to be realized in the coming two-three years time, the solutions for pit lining are solved by steel sheet solutions that are rather expensive yet. Steel tank storage for large-scale applications are mature, but very expensive.

4.3. Other considerations

Beyond the technological subjects, socio-economical changes are necessary for the dissemination of CSHPs. In Denmark, economical and political uncertainties for DH-operators makes it difficult to motivate for such large investments as the one necessary for large-scale solar heating, even the energy-prices are heading fast towards competitive applications. Willingness from regulators is a necessity for the success dissemination of this already successful technology. To get on this track, it is necessary to prove the relevancy of the technology in a broader perspective of energy planning. Here the questions are: Is District Heating (DH) a relevant technology in a sustainable energy system? Can CSHP with or without large-scale DH fit into a sustainable energy system? How do we optimize heat supply contra e.g. thermal insulation on the demand side? This is some of the work to do in the future to get towards a sustainable energy system and society, the real necessity.

All these problems have to be solved, if the targets of the international agreements are to be met. Renewable energy sources are the only inexhaustible energy sources there is. Solar thermal meet the low temperature demands already today. Other applications demand high temperatures that can be met by high efficient collector technologies to be demonstrated in systems in the next years. Large share demand large storage capacities that showed up to be more demanding than it was expected. Here developments in material for lining and thermal insulation are central.

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