FINAL TECHNICAL REPORT

CONTRACT N^{o}: NNE5-2000-00490

PROJECT N^{O}: NNE5-2000-00490

ACRONYM: SUNSTORE 2

TITLE: Solar Thermal and Long Term Heat Storage for District Heating Systems

PROJECT CO-ORDINATOR: Marstal Fjernvarme, DK

PARTNERS:
PlanEnergi, DK
Ramboll, DK
ARCON Solvarme A/S, DK
CIT Energy Management AB, S
Universitaet Stuttgart, Institut fuer Thermodynamik und Wärmetechnik

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1 Publishable Final Report

1.1. Executive Summary

In 2000 Marstal Fjernvarme situated on the island of Ærø in Denmark was the owner of 9 043 m^2 solar collectors producing 16% of the annual heat consumption. A new project, SUNSTORE 2, supported by the European Commission (5th Framework) and the Danish Energy Agency has added 8 019 m2 of ARCON HT (DK) solar collectors, 881 m^2 flat-plate collectors from GJ-Teknik (DK), 103 m^2 roof-module collectors from Wagner (DE), 211 m^2 focusing collectors from IST (US) and 108 m^2 evacuated tubes, Solamax AST-20MD (GB).
The range of solar collectors represent the most competitive collectors to the ARCON HT collector and thus makes it possible to compare production and maintenance costs for solar collectors producing heat to a district heating system.
Except the Wagner collector all the solar collectors are ground mounted. Storage capacity for the solar collectors includes a 2100 m^3 steel tank, a 3500 m^3 sand and water filled pit heat storage with PEX-pipes for heat exchange and a new 10.000 m^3 water filled pit heat storage with floating cover.

The project has the following objectives and results:

1. **The design of a pit heat storage to be constructed at less than 67 €/m^3 at a size exceeding 10 000 m^3 and less than 30 €/m^3 at a size exceeding 50 000 m^3 (price level 2001).**
   The result is, that the 10 000 m^3 pit heat storage in Marstal is constructed at 67 €/m^3 and using the same prices/unit a 100 000 m^3 storage can be constructed at 31 €/m^3 (price level 2004)

2. **The design of a ground mounted flat-plate collector with an efficiency improvement of at least 10% without a corresponding increase in the price.**
   The results is an efficiency improvement of 19% and a 5% higher price. Thus the cost-efficiency has been 13% better.

3. **Demonstrate a 10 000 m^3 pit heat storage with floating cover and a 10 000 m^2 solar collector field including demonstration of different flat plate and focusing solar collectors.**
   The 10 000 m^3 pit heat storage is built and six different solar collectors are demonstrated as mentioned above.

4. **Integration of solar heating with a 30% solar fraction in a conventional district heating system. Price of energy 0,045 €/kWh.**
   In Marstal 8 019 m^2 of new ARCON-HT collectors and 10 000 m^3 pit heat storage has been established for less than 2,28 mio. €. The production is around 3 800 MWh/year. If the financial costs are 6,7%/year, the heat price is 0,04 €/kWh. This is calculated for the last 8 000 m^2 in a 19 000 m^2 plant covering 30% of the annual production. A calculation for a new plant of totally 19 000 m^2 covering 30% will show an even lower heat production price/kWh.

Monitoring results can be found at www.solarmarstal.dk.

The results of the project mean that 30% of the demand for heat in a district heating system in Northern Europe may be covered by solar heat with the same profitability that has so far been ap-

plied to a coverage of 10-20% with solar energy. Also the cheap pit heat storage and solar collectors will be usable in existing or new hybrid district heating and cooling systems in Southern Europe.

1.2. Publishable synthesis report

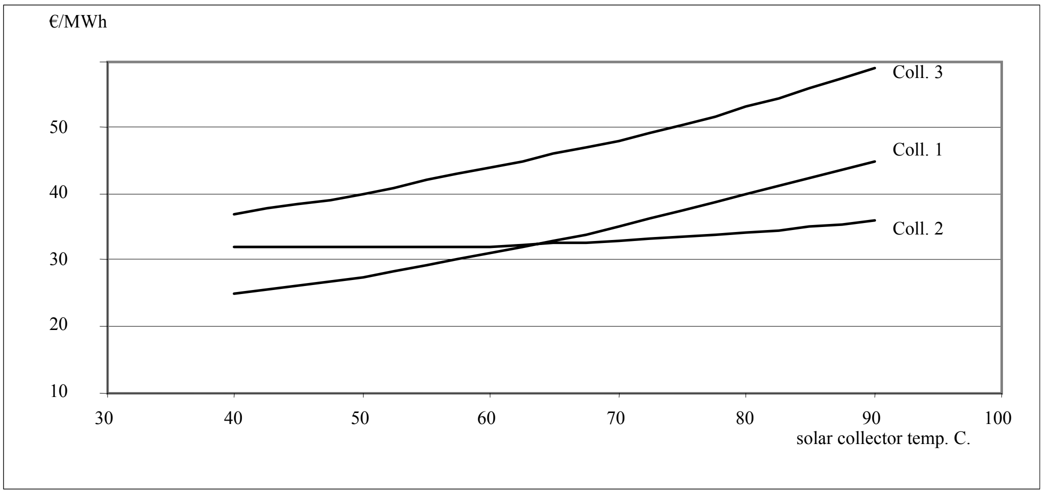
The main topics of the SUNSTORE 2 project has been to develop a new and better ARCON-HT flat-plate ground mounted solar collector, to develop a cheap pit heat water storage and to demonstrate at least 8 000 m2 of the new solar collector, the most competitive collectors of other types and a 10 000 m^3 pit heat storage in the town of Marstal, Denmark.
When the project started in 2001 9 043 m^2 of solar collectors established between 1996 and 2000 were already in function

The Marstal plant before extension.

Optimising the HT-collector

The first 9 043 m2 of solar collectors in Marstal are ARCON´s HT-collectors with efficiency:
η_o = 0,76, k_1 = 3,5, k_2 = 0,02. The optimisation of the collector has taken place during and in between 3 workshops arranged for the project partners in autumn 2001. During the workshops possible changes in cover, convection stop, absorber type and insulation were discussed. In between the workshops the efficiency graph and the cost for each change in collector construction was calculated.
Knowing the efficiency graph of the collector the yearly production was calculated for solar collector temperatures of 40, 50, 60, 70, 80, 90 and 100^{o}C. The calculations were carried out with the Danish Test Reference Year (TRY) and one-hour steps either in TRNSYS or a spreadsheet developed in EXCEL especially for this purpose. Calculating the price/kWh the investment/m^2 was transformed to cost/year by using a factor of 0,067 or the same as the average costs for a 20 year annuity loan if inflation is 3%. Finally the price in €/MWh was calculated by dividing costs/year with the yearly production.

The results was curves like this



Example of production prices/kWh for different solar collectors at different mean heat temperatures.

As can be seen from the example solar collector 1 has the best economy for solar collector temperatures less than 63 ^oC . For higher temperatures solar collector 2 has the best economy.

Efficiency graphs, price calculations for a 4 000 m^2 plant and calculation of production prices have been done for the following variations of the HT-collector.
Cover: Two different glass types were calculated with and without anti reflex treatment.
Convection stop: a calculation without teflon was carried out because this cheaper solar collector might be competitive at lower temperatures.
Absorber: Three different types of absorbers were calculated.
Insulation: Two different types of insulation were calculated.

Finally a combination of the best solutions was chosen. The result was that the same combination was the best overall in the temperature range between 40 ^oC and 80 ^oC and ARCON then built the new HT-Collector.

The new HT-collector included the following changes in the existing ARCON HT-collector:

- antireflex treated Solatex cover
- new Niox absorbers
- Industri 40 insulation

The Danish Technical University measured the efficiency. To compare the results, the HT-collector produced by ARCON 1998-2001 (HT-NIOX) was tested under the same conditions.

The measured efficiency graph for the new HT-collector was : η_o = 0,81, k_1 = 2,57, k_2 = 0,0079. For the older HT-collector (HT-NIOX) the efficiency graph was measured to: η_o = 0,75, k_1 = 3,07, k_2 = 0,005.

TRNSYS calculations for the new 8000 m^2 area with HT-collectors in Marstal show a production of 402 kWh/m^2 with the efficiency graph for the older HT-collector (HT-NIOX) and 477 kWh/m^2 with the efficiency graph for the new HT-collector. The production from the new HT-collector is thus calculated at 19% higher. The price for the new collectors is 5% higher than the price for the old collectors. Thus the cost-efficiency was calculated to be 13% higher.

Finding the most competitive solar collectors.
With the purpose of selecting solar collectors for the demonstration field, prices for 4 000 m^2 collector fields along with their data for efficiency calculations were found for the following:

- three ground-mounted flat-plate collectors.
- two flat-plate collectors produced as roof-modules.
- four ground mounted collectors produced as evacuated tubes.
- two types of ground-mounted focusing collectors

The best collectors in the above mentioned four categories were:
- Flat plate collectors: GJ Teknik, DK
- Roof modules: Wagner SunSelect, antireflex treated, DE
- Evacuated tubes: Thermo Sol (Solamax AST-20MD), UK
- Focusing collectors: IST, US

It was decided to demonstrate the following collector areas

Collector type	m^2
ARCON – HT, new	8 019
GJ-Teknik, new	881
Wagner	103
Termomax	108
IST	211
Total	9 322

Design and building of the 10 000 m^3 pit heat storage.

Design
Since the beginning of the 1990'es work on the development of seasonal heat storages has been carried out in Denmark. The superior economical aim has been to reduce construction costs to less than 35 €/m^3 (price level 2004) water equivalent for storages larger than 50 000 m^3. The only storage type which appears to give a solution to this demand is pit heat storage dug into the ground. A Danish test storage of 1 500 m^3 (Ottrupgård) was constructed in 1996.
The test storage was constructed with bottom and sideliner of 85 cm clay, covered on the outside with an EPDM-rubber liner which was not tight – on purpose – and the cover was made as a floating cover using cold store wall elements. The experiences from the test store have been that the clay/EPDM liner is expensive to construct. Furthermore it is difficult to make it sufficiently tight and to localise and repair leakages. The floating cover consisting of cold store wall elements is an expensive construction, too, which requires extensive joint work and taping between the elements, to prevent the seeping in of moisture.

Therefore the aim of the design work with the 10 000 m^3-storage in Marstal was to reach a simpler and cheaper construction. The preference would be a single welded plastic liner on bottom and sides and a simple floating cover, also using a plastic liner for the underneath.

Choosing the side- and bottom liner
Owing to the above reasons the design work started out with a forced long term test of the liner types we presupposed to be the most adequate. The liners were tested in the Danish Technological Institute in Copenhagen under temperatures of 100, 107 and 115 ^oC. The keeping qualities were mainly defined as the point of time when the extension that causes leakages was reduced to 50%.

The resultants were the following

	Lifetime	
Temp ^oC	Liner 1	Liner 2
100	400 days	530 days
107	200 days	330 days
115	120 days	180 days

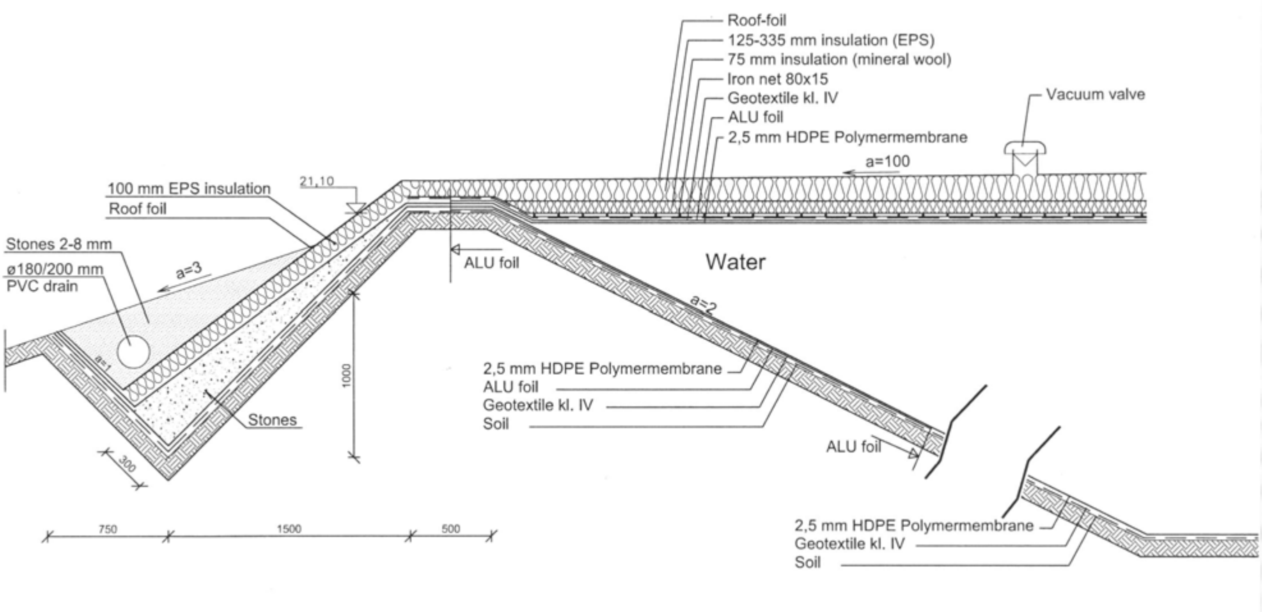
Lifetime for liners
Liners 1 and 2 are both HDPE liners.
The lifetime for the liners under the temperature conditions expected to be valid in the top meter of the storage has been calculated to 22,6 years (liner 1) and 24,3 years (liner 2). Thus both lines proved applicable.
Furthermore there is a likelihood that the watertightness will be preserved for yet some time provided the liner is not submitted to physical load and that the lifetime may be extended by preventing access of oxygen.
Therefore it was decided to use HDPE for side and bottom liners.

The cover solution
The cover is by far the most expensive part of a pit heat storage. Since constructing the Ottrupgård storage efforts have been made in several projects to find a solution with lower costs. During these projects tests have been carried out with a floating cover built up using either PP modules or a stainless steel cover. The plastic solution was the cheapest but PP will not keep for 20 years under the temperature conditions to which the cover is exposed in Marstal. The HDPE liners tested will keep but they are too rigid to be folded into modules. Therefore a new solution had to be constructed in which the cover is one big HDPE liner, placed on the surface of the water, shaped like a roof construction. The cover has been built up using the following layers (from the bottom up)

- 2,5 mm HDPE
- Vapour barrier (vapour diffusion of the HDPE liner would cause condense in the insulation of the cover construction).
- Geotextile (for protection of the vapour barrier and liner).
- Steel grid (to maintain the shape of the cover during extensions due to temperature).
- 75 mm mineral wool
- 125-335 mm EPS insulation.
- Roof foil with ventilation caps.

Solution for the edges

The storage has been constructed with earth balance. Therefore it is surrounded by a bank of varied height. Both the cover liner and the side liner are locked in a ditch outside the bank. The upper part of the storage is equipped with a vapour barrier on the inside of the sideliner to avoid condense in the bank. The bank is insulated on the outside with EPS, as the U-value would be considerably higher in this place compared with the cover construction.The total solution is shown below.



Lock ditches and cover construction.

Pipe penetrations

Intake and outlet from the storage takes place through two pipe penetrations in the upper part of the side liner. In order to make the penetration waterproof an HDPE sheet has been welded on the liner. The HDPE sheet is penetrated by two lining pipes which have been welded on. The intake and outlet pipes run in each their lining pipe with silicone injected between the intake/outlet pipes and the lining.

Constructing the storage

The work was initiated in 2003. On the 4th of July the excavation in crude soil had finished after which placing the bottom and side liner on geotextile could take place. The liner was welded with a double hem and pressure tested thereafter. The laying out was finished on the 18th of July.

During the laying out the weather was very hot with sunshine. Furthermore the liner was not sufficiently held in the top. Therefore it slid down and had to be pulled in place and to be secured with sand bags.

Filling water into the system was started on the 29th of July but was interrupted when the water had reached 1 m because heavy folds were observed in the liner. The liner supplier viewed the folds and approved that the filling up continued until the storage was full on the 25th of August.

After that the bottom liner for the cover was welded ashore and gradually placed on the water surface. It took three working days to establish the bottom liner for the cover after which the building of the cover could take place. That happened without problems except for an interruption of 5 days because a loss of water in the storage was detected. The joint between the HDPE sheet and the lining pipe was not tight in one pipe penetration. After a few days' contemplations it was agreed to try and solve the problem by placing an HDPE box on the outside of the intake pipe and fill the cavity with silicone. Thereafter the construction of the cover was completed. The construction of the cover lasted 8 working days.

All in all the construction of the storage was faster and more unproblematic than we had feared.

Economy

Total costs for construction of 10 000 m^3 storage ended at 670 000 € or 67 €/m^3 . However, it is more interesting to calculate at which price at storage of 100 000 m^3 may be constructed. That has been attempted below.

	Costs (1000 €)	**Costs (€/m^3)**
Excavating	761	7,6
Side- and Bottom liners	184	1,8
Cover	1 516	15,2
Draining	26	0,3
Intake and outlet	268	2,7
Control system	67	0,8
Other costs 10%	282	2,8
Total	**3 104**	**31**

Estimated plant price for 100 000 m^3 storage incl the intake and outlet arrangement.

Thus it seems to be possible to reduce construction costs to less than 35 €/m^3. Calculations in tabel 1 has been made with same price/unit as the 10 000 m^3 storage.

The Marstal plant after extension.

Monitoring System

The Marstal Solar Heating Plant is equipped with an extensive monitoring system. In the hydraulic system temperature sensors, flow meters, pressure sensors etc. as well as separate heat meters are installed in all relevant places. In the solar collector fields additional temperature sensors are installed at the outlet of every single collector row. In the new Arcon field one collector row is equipped with additional temperature sensors between the single collectors.

The heat stores are also occupied with numerous monitoring sensors. The new 10 000 m³ water filled pit heat store is equipped with temperature sensors in- and outside the storage volume, heat flux sensors in the top layer as well as a moisture sensor and temperature sensors within the floating cover to get information about the long-term heat and steam transport processes through the wall constructions.

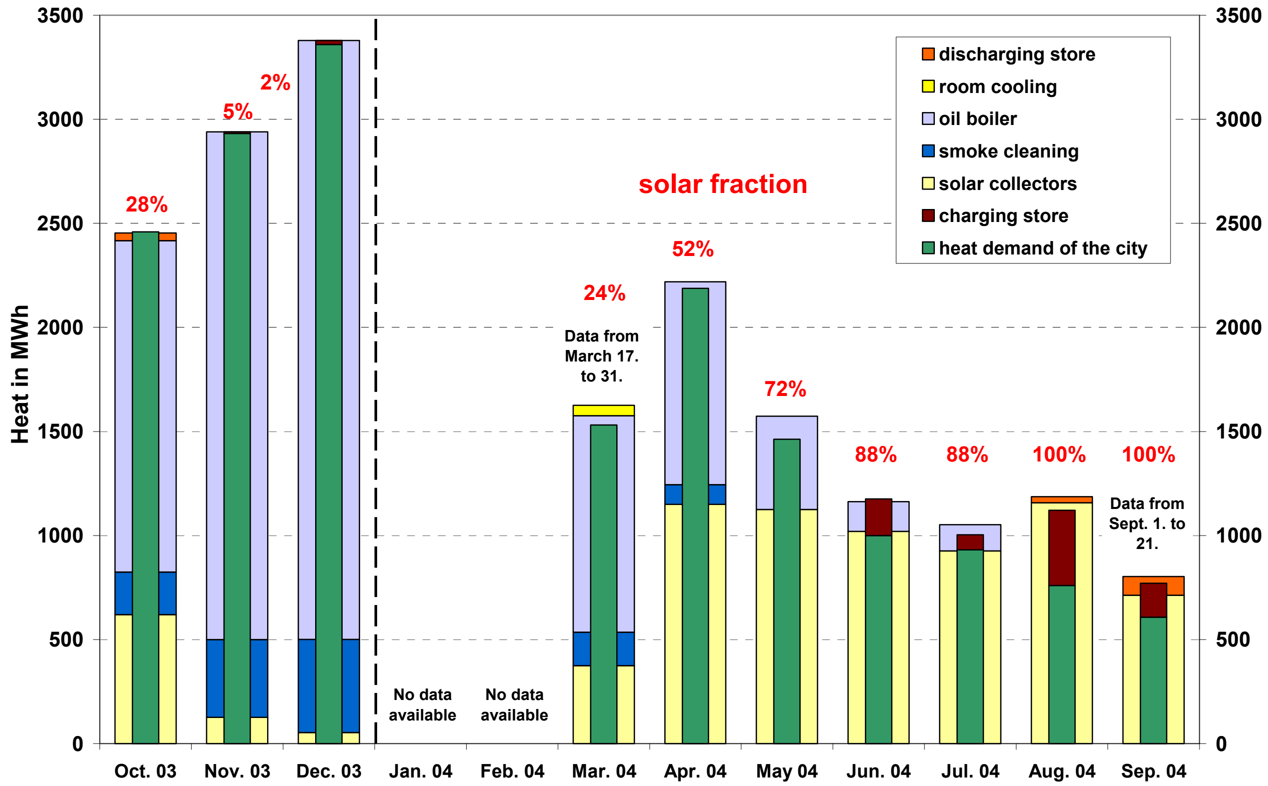
Climatic data is recorded by a couple of Pyranometers in the different collector field orientations, wind speed and wind orientation sensors as well as an ambient temperature sensor. The data is recorded, processed and stored by the control system of the plant in combination with a database.

With the information from the monitoring system, contributions of the single heat producers like the different collector fields, boilers etc., and the total heat balance of the district heating system can be calculated. Also the operation and e.g. the hydraulic adjustment of the single collector rows can be observed.

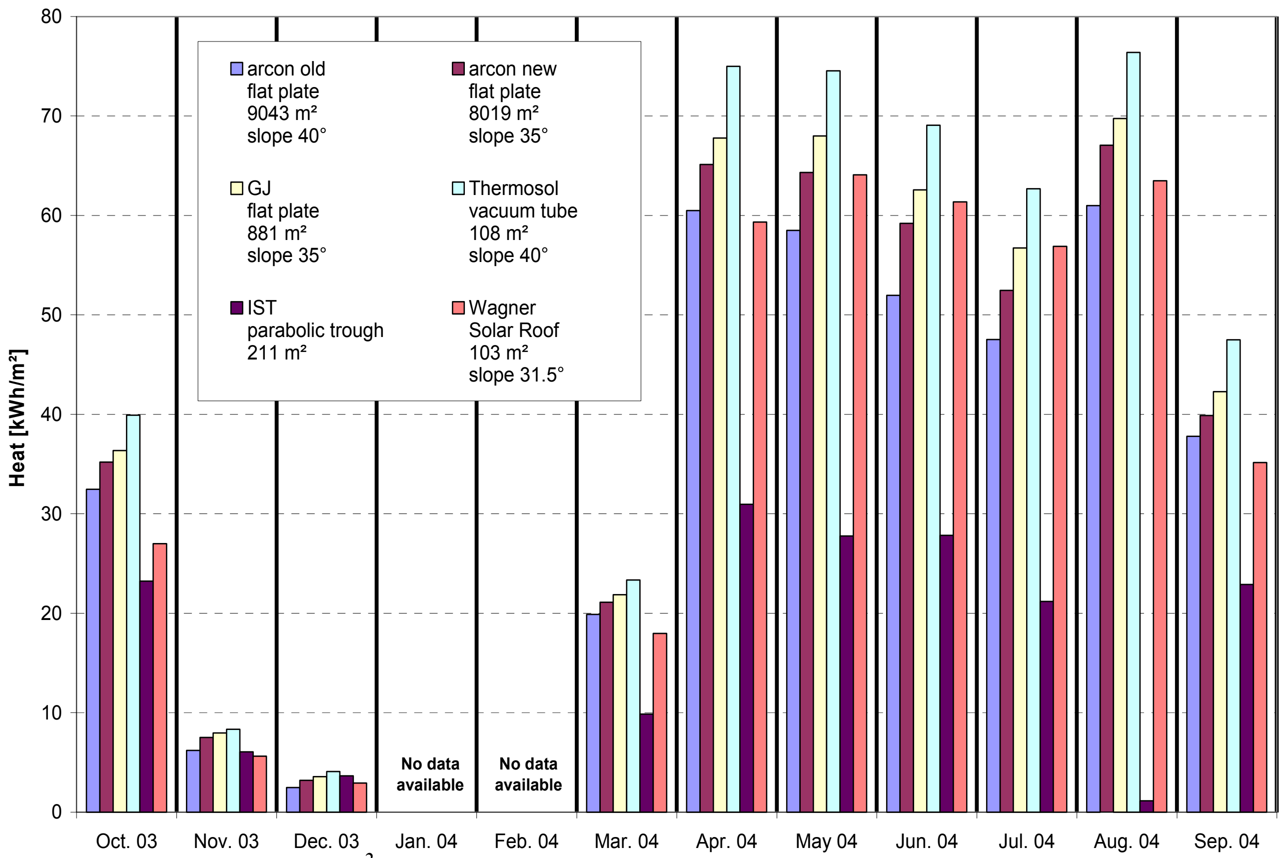
The measurements from inside and outside the two seasonal heat stores deliver valuable information about the long-time behaviour and the efficiency of these components that are still under development. Seasonal heat stores e.g. have higher heat losses in the first three to five years of operation because the surrounding ground has to be heated up to steady-state operating conditions. The temperatures from the surrounding ground give information about this effect and about the influence of possible overlaying effects like groundwater movements.

The within the SUNSTORE 2 project period added collector fields started operating end of February 2003. The monitoring equipment was first connected in September the same year. From January to mid of March 2004 a problem with the monitoring database server prevented a recording of data.

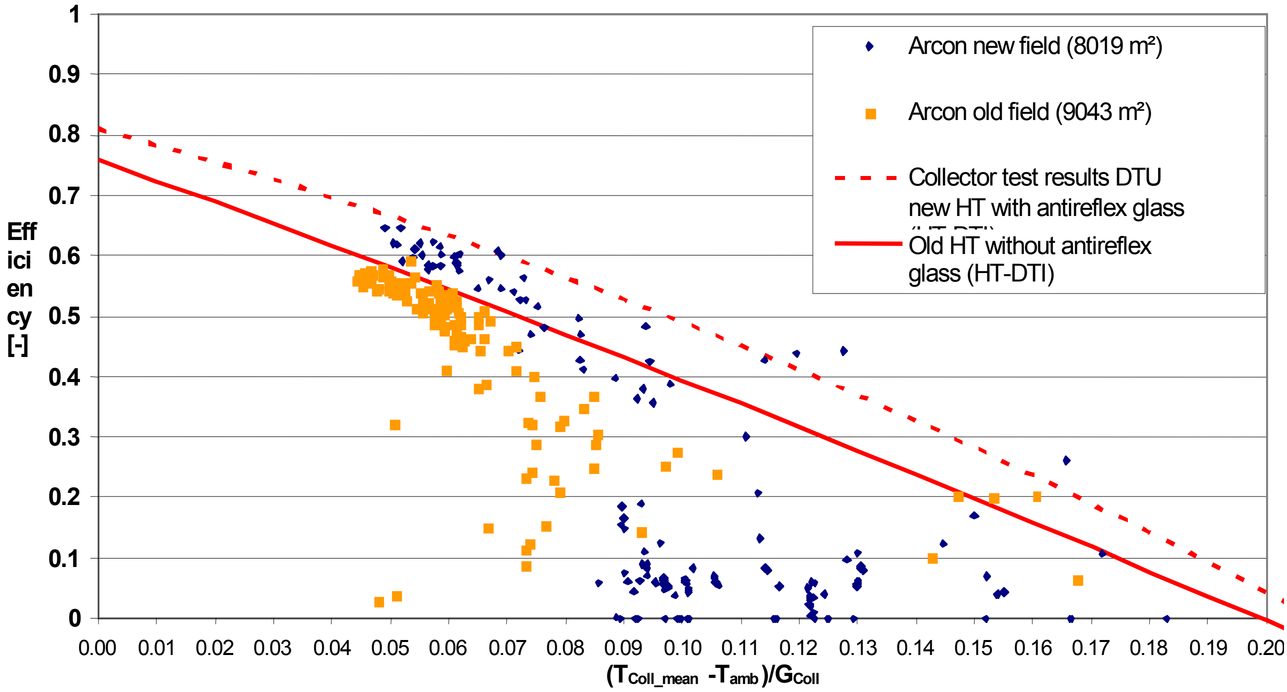
In the following are selected monitoring results.



System heat from October 2003 to September 2004 according to heat meter data.



Solar heat production per m^2 collector area.

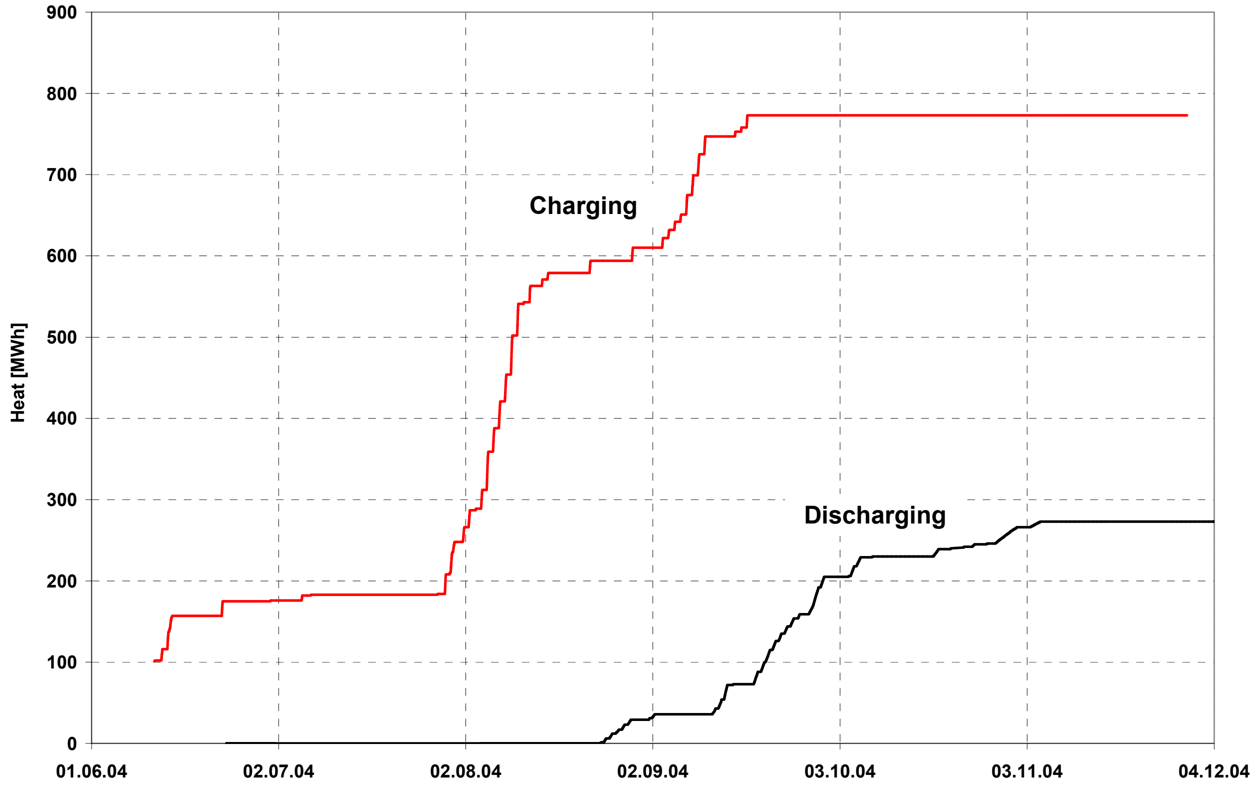


Collector field efficiency Arcon collector fields.

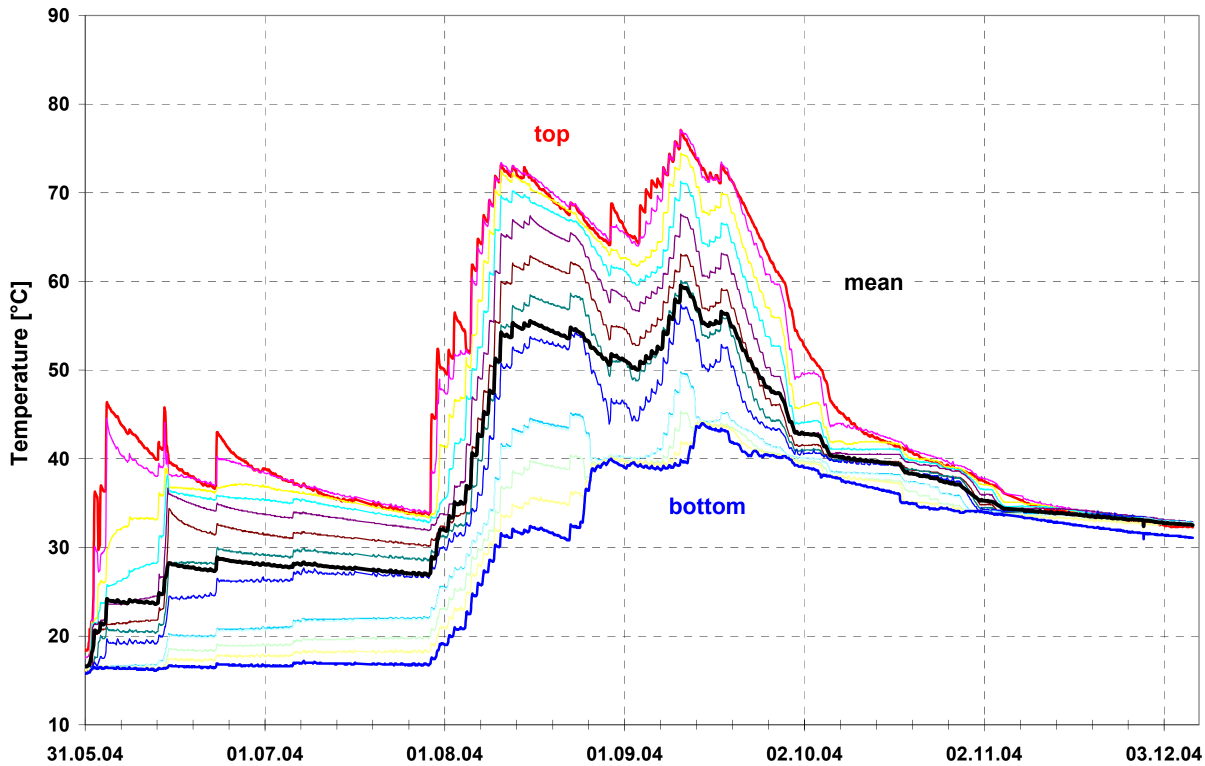
The efficiency values from the measurements are slightly below the efficiency curve from the collector test. This is because the test was done for one single collector; the measurement in Marstal is done for the whole collector field including the thermal losses of the piping within the field and to the heat exchanger. The most frequent operation conditions are between $\Omega = 0.04$ and $\Omega = 0.08$.

10 000 m³ Pit Heat Store

The pit heat store went into operation in May 2004. The main charging took place end of July and beginning of August, where about 430 MWh of heat where charged into the store. After a short discharging period end of August another 163 MWh where charged in September. Altogether 773 MWh where charged into the store in 2004, 273 MWh where discharged until end of November. The change in the internal energy content was estimated to 186 MWh between end of May and end of November. With these numbers an efficiency of 59 % can be calculated for the store. However, it has to be taken into account that the heat losses to the surroundings are higher in the first years of operation than in the long run.



Charging and discharging of the pit heat store



Charging and discharging of the pit heat store (temperatures)

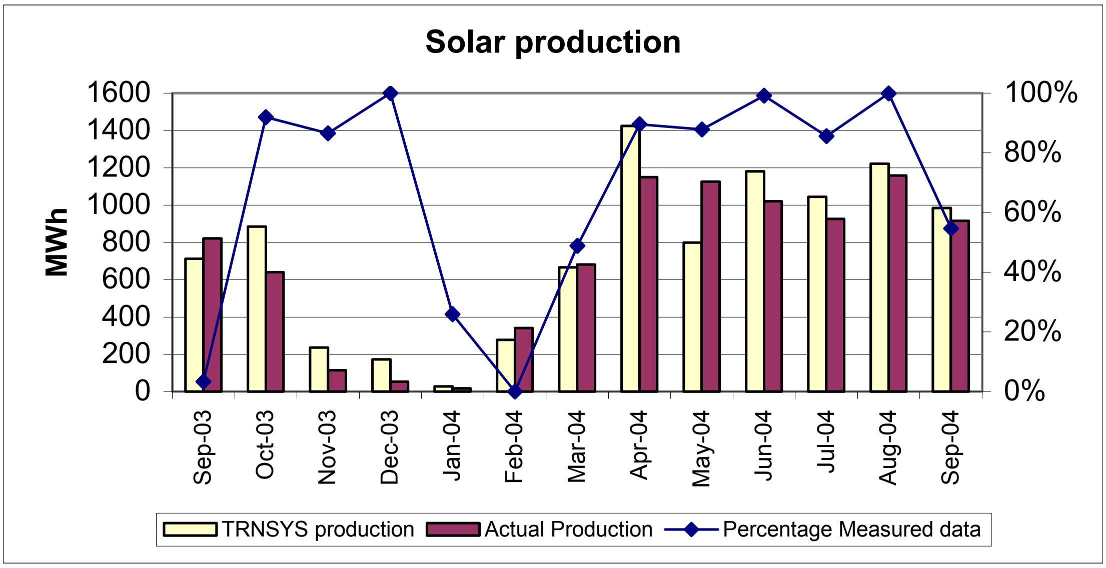
The ground around the pit heat store is heated up due to the transmission heat losses through the side walls and the bottom. The yearly mean temperature of the surrounding ground will increase in the first years because of these heat losses. After a start-up period of three to five years, where the yearly heat losses will continuously decrease, the yearly mean ground temperatures will not change anymore and the store is operating under steady-state conditions.
Because of the start-up period, the temperature changes in the store and the temperature changes at the ground surface the temperature development around the store will have a seasonal and a long-term component. The seasonal component will follow the temperature development at the surface and inside the store with a delay.

TRNSYS calculations

Comparison between Calculations and Measurements.
In the detailed design of the new solar collector field was developed a TRNSYS model, which included the whole Marstal District heating plant, that is with both the new and the original collector field, the steel tank and the new pit storage. The model was developed in the TRNSYS software, and simulated the system over a period of four years. The long simulation period was chosen in order to have the pit storage in balance with the surrounding earth.

The TRNSYS model has subsequently been altered. In the new model the measured data now replaces the original TRNSYS data where measuring data are available.

Comparison, Monthly values

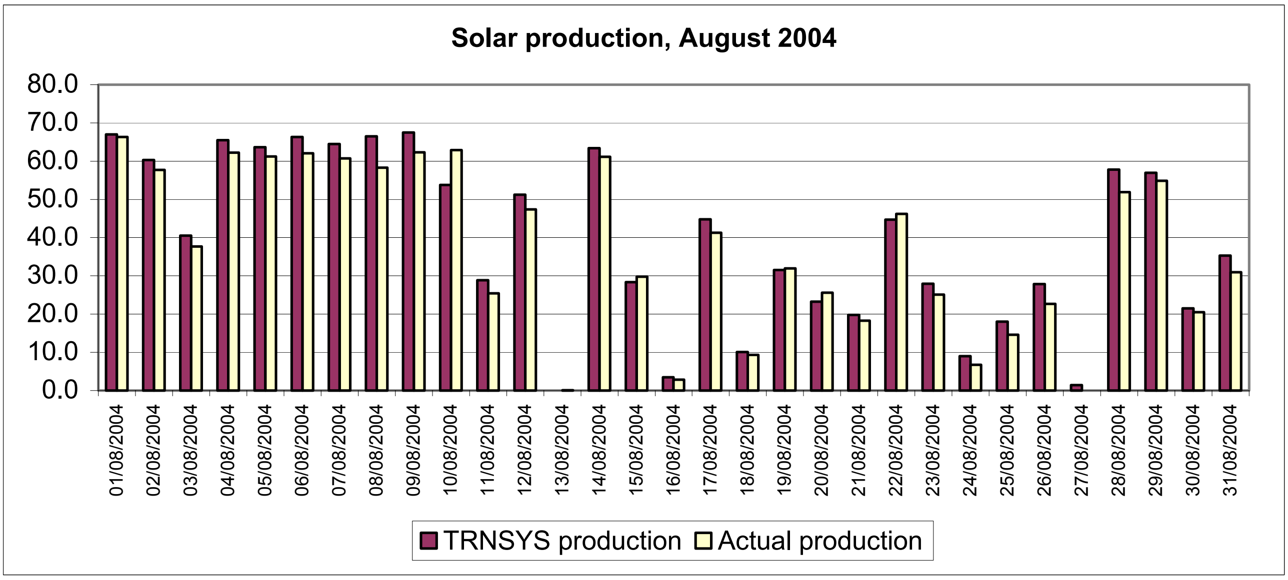


Solar production compared with calculations

Taking a closer look at a single month, August 2004, it appears that the production calculated in TRNSYS, based on the measured solar radiation is in average round 5% higher than the actual production. One reason for this higher production can be the fact that the measured radiation is without array shading. In the original TRNSYS model is included array shading, but due to the nature of the measured radiation data, it was not possible to include it in the altered model.

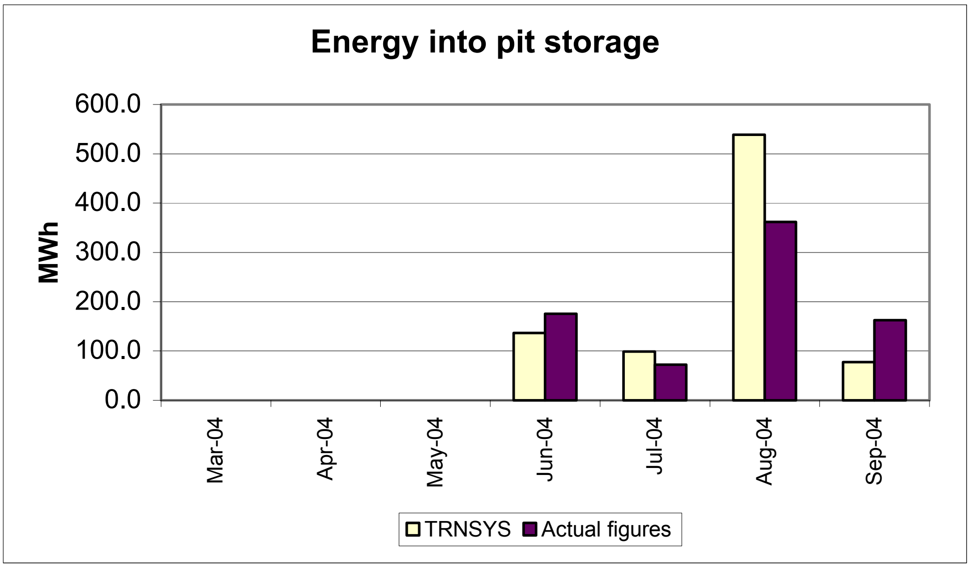
The impact of array shading, i.e. the rows of collectors are in shadow of the row in front, has been analysed earlier in this project. From those calculations can be extracted that the impact of array shading is approx. 4% in August.

Thereby it can be concluded that the TRNSYS model generates a solar production close to the actual production in August.



Solar Production, August 2004.

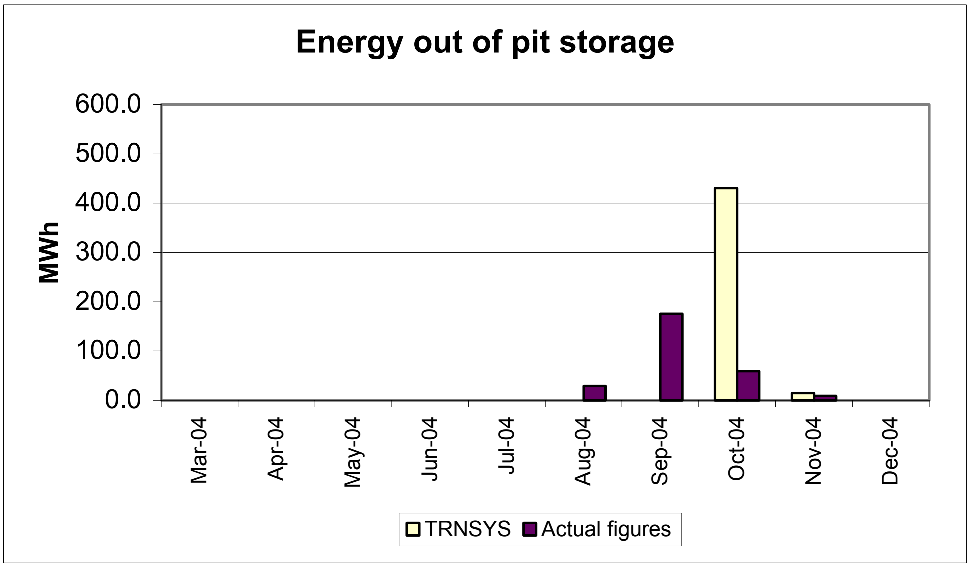
Energy in and out of Pit Storage
In relation to the pit storage the following data have been calculated and measured:



Energy into pit storage

Comparing the TRNSYS production with the actual energy input there is some fluctuation. Summing up the figures from June to September TRNSYS calculates an energy input of 851 MWh, where the actual input was 773 MWh.

When it comes to energy out of the storage the following figure appears. The period has been extended to the end of the year. Here the fluctuation is even more distinct.



Energy out of pit storage

Adding the figures from August to December the model has an energy outtake of 446 MWh, where the actual outtake was 273 MWh. The energy loss in the storage, calculated as difference between input and output, was in TRNSYS 406 MWh and in the actual storage 500 MWh. Thus the loss from the actual storage is 1/3 higher than the loss calculated in TRNSYS.

2 Detailed Final Report

2.1. Objectives and strategic aspects

The scientific and technical objectives were:

- The design of a pit heat storage to be constructed at less than 67 €/m^3 at a size exceeding 10 000 m^3 and less than 30 €/m^3, at a size exceeding 50 000 m^3.

- The design of a ground mounted flat-plate collector with an efficiency improvement of at least 10% without a corresponding increase of the price.

- Demonstrate a 10 000 m^3 pit heat storage with a floating cover. Demonstrate a 10 000 m^2 solar collector field, divided in parts adapted for different levels of temperatures. Hereby both different types of ground-mounted flat-plate collectors will be demonstrated as well as focusing solar collectors. Thus district heating companies, for example, will be able to receive information about performance and experiences concerning maintenance under identical conditions for different types of solar collector fields. Heat storage and solar collector field will be demonstrated in the town of Marstal, Denmark.

- Integration of solar heating in a conventional district heating system. Solar fraction 30%. Price of energy 0.045 €/kWh.

Accomplishment of these aims will mean that 30% of the demand for heat in a district heating system may be covered by solar heat with the same profitability that has so far been by applied to a coverage of 10-20% with solar energy. In doing so the European solar heat market for large scale plants will be doubled.

Contribution of Programme / Key Action Objectives/Generic Actions

The Council Resolution on renewable energies of May 1998 advocates

- the construction of 100 areas to be supplied with 100% renewable energy.
- the construction of 100 mio. m^2 solar thermal collectors by 2010. District heating is stressed as being the most promising area for large scale plants.

SUNSTORE 2 contributes to both the above aims as the demonstration plant will be constructed in an island aiming at 100% renewable energy and solar heating for district heat supply will be demonstrated.

Within the working area of Energy, Environment and Sustainable Development SUNSTORE 2 contributes to the following areas within key Action 5 and 6.

Development of other sources for renewable energy (5.2.5.) to provide a substantial contribution for the aim of the programme concerning 12% RE supply. So far the solar heat plants have been divided in plants using short term storages covering 10-20% of the annual demand for room heating and hot water, and plants with seasonal heat storages covering more than 50% of the annual demand. Up till now only plants using short term storage have been considered profitable in a foreseeable future. However, SUNSTORE 2 will demonstrate that a solar fraction of 30% may be obtained in block heating and district heating systems without deteriorating the economy. With the construction prices of today, heat can be produced at 0.045 €/kWh. Within a 5 year period the heat may be produced at 0.035 €/kWh by implementing further efficiency measures in production and solar collector technology.

In the APAS project "Large Scale Solar Heating Systems" (RENA CT94-0057) a total market potential for solar heat has been estimated at 250-400 mio. m^2 . Of this more than 20% (50-80 mio. m^2) are plants supplying 10-20% coverage of the heat demand in block heating and district heating plants. Provided the solar fraction is increased to 30%, a further 50-80 mio m^2 may be established in large systems, corresponding to a heat production of 25-40 TWh/year.

Developing hybrid systems (5.3.2.).
In the demonstration plant solar heat and long term storage are combined with production of heat based on waste oil. The system is very flexible to a further extension up to 100% supply of renewable energy, whether that be more solar heat, wood chip fuelled district heating or CHP or a combination of the above mentioned with a heat pump. The flexibility exists due to the long term heat storage. Marstal Fjernvarme will host the demonstration project and extend it to 100% supply of renewable energy within a few years.

It will be possible to combine solar heat and long term heat storage with all kinds of existing heat supply unless that is based on an obligatory consumption of waste heat in the summer (i.e. from waste incineration). On the other hand heat storage without solar heat might often be relevant in that case.

Developing heat storages (6.3.3.)
SUNSTORE 2 intends to demonstrate a 10 000 m^3 test pit heat storage, to be constructed for less than 67 €/m^3 in this size but for less than 30 €/m^3 when the storage exceeds 50 000 m^3. At a large scale the pit heat storage combined with solar heat will be able to cover 50% of the heat demand at a price of less than 0.05 €/kWh. Therefore, developing this type of storage would make a solar fraction of 50% possible.

Develop efficient components (6.5.4.).
Ground mounted flat plate collectors will be further developed in order for the production to be increased with at least 10% without a corresponding increase of the price. The existing control system will also be further developed.

Dissemination

The results of SUNSTORE 2 will be immediately useful in similar projects in other European regions. On their own and together the proposers will market the concept in Europe.

Through the national district heating associations in Northern Europe Marstal District Heating will inform the district heating companies and the block heating centrals about the Marstal plant and the possibilities for following the project in the Marstal website or visiting the demonstration plant, see different types of solar collectors in operation and be told about the operation and maintenance experiences and the plant performance. Ramboll and PlanEnergi will market the concept as advisors to clients first and foremost in Northern Europe. ARCON, which is the world's largest supplier of ground mounted flat-plate collectors will intensify its marketing to district heating and block heating centrals in Northern Europe. Universitaet Stuttgart and CIT Energy Management will disseminate the results further to producers of roof mounted collectors to allow them to become aware of the possibilities for increasing the solar fraction to 30%. In that way the project will contribute further to the volume increase for solar heat.

2.2. Scientific and technical description of the results.

In the following chapters the work and results in the project are described chronologically.

2.2.1. Localisation of the plant and approval from authorities.

In placing the plant, 2 main demands needed to be met

- Development of the original solar field must be carried out so the collected solar field appears harmonic and as a whole.

- The pit heat storage must be placed in an area where it is not subject to running ground water

- The pit heat storage must be placed in an area where the soil conditions allow a construction at 1:2 when excavated.

The last demand was the most critical as large areas had previously been found containing plastic clay that would allow a maximum slope of construction of 1:4.

Therefore the Danish company of GEO was requested to point out the best placement of the pit heat storage. The pointing out was executed by first carrying out geo-electrical measurements all over the possible positions for the plant and after that carry out test borings. The result was the recommendation for position shown in fig. 2.1

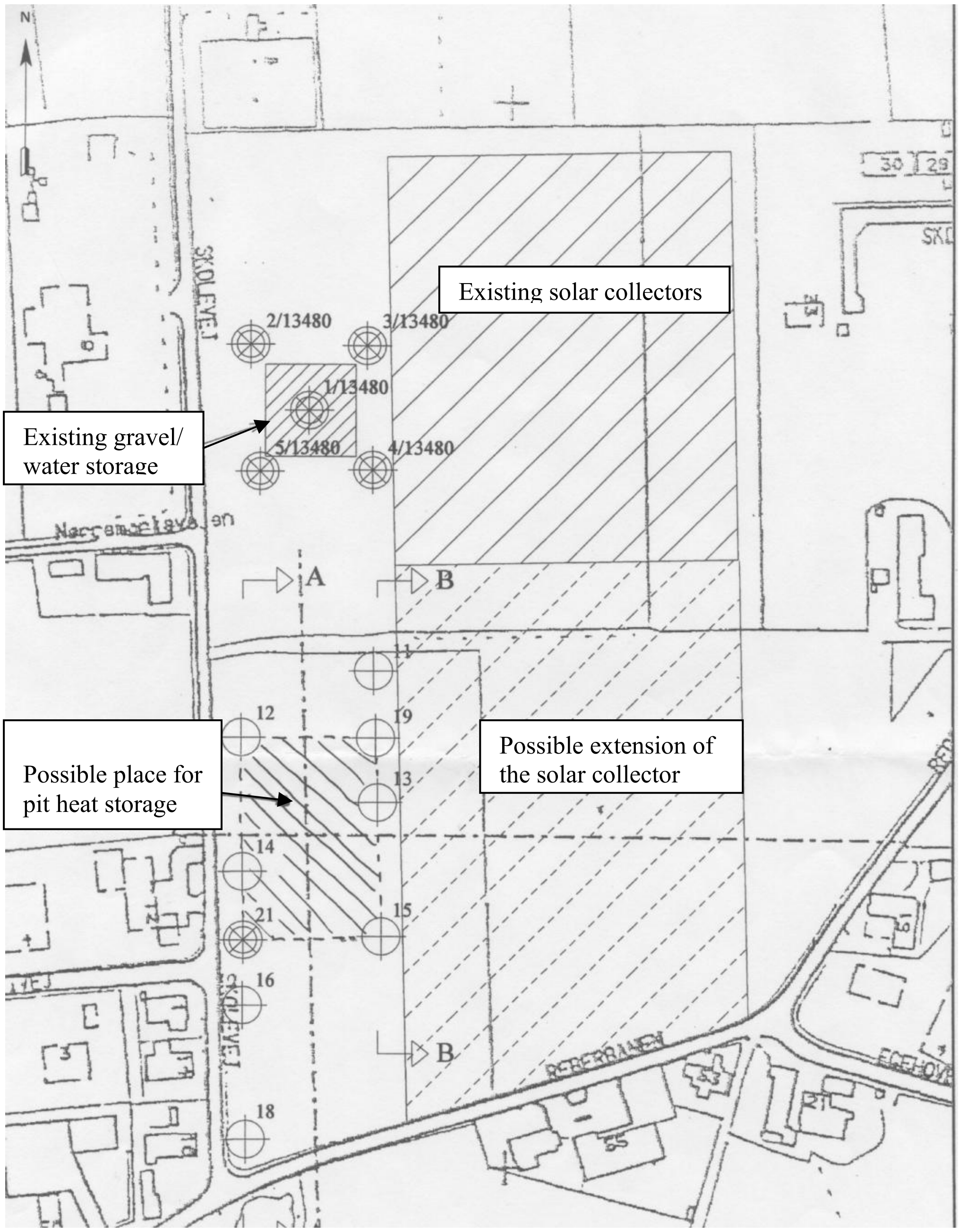


Fig. 2.1. Recommendation for position of pit heat storage.

Authorities' approval

After the position of the pit heat storage had been decided, the municipality of Marstal elaborated a local plan for the area in which the solar heaters and the pit heat storage would be placed. The local plan was sent in public hearing and thereafter approved by the municipal council in March of 2002.

Parallel with this, Marstal District heating made an application for project approval according to the Law of Heat Planning. The application was approved by the municipal council, and when the Danish Energy Agency did not have any objections either, the project approval was ready in march of 2002.

2.2.2. Detailed design of the solar thermal plant

The design phase included optimising the HT-collector, finding the most competitive collectors and designing the whole collector field.

Optimising the HT-collector

The first 9 043 m2 of solar collectors in Marstal are ARCON´s HT-collectors with efficiency: η_o = 0,76, k_1 = 3,5, k_2 = 0,02. The optimisation of the collector has taken place during and in between 3 workshops arranged for the project partners in autumn 2001. During the workshops possible changes in cover, convection stop, absorber type and insulation were discussed. In between the workshops CIT Energy Management (Jan-Olof Dalenbäck) calculated the efficiency graph for each change in collector construction by using the software of DIMSOL. ARCON calculated the cost of the change and PlanEnergi compared competitiveness of the changed collector to the collectype already placed in Marstal.

To compare competitiveness of different solar collectors PlanEnergi has calculated the production price per kWh at different collector temperatures. Knowing the efficiency graph of the collector the yearly production was calculated for solar collector temperatures of 40, 50, 60, 70, 80, 90 and 100^{o}C. The calculations were carried out with the Danish Test Reference Year (TRY) and one-hour steps either in TRNSYS or a spreadsheet developed in EXCEL especially for this purpose. Calculating the price/kWh the investment/m^2 was transformed to cost/year by using a factor of 0,067 or the same as the average costs for a 20 year annuity loan if inflation is 3%. Finally the price in €/kWh was calculated by dividing costs/year with the yearly production.

The results will be curves like this

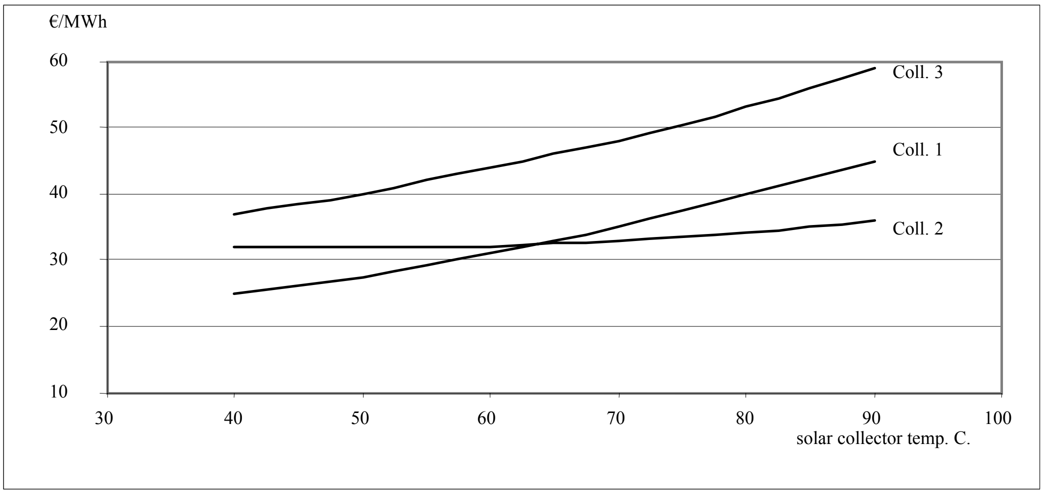


Fig. 2.2. production prices/MWh for different solar collectors at different mean heat temperatures.

As can be seen from the example in Fig. 2.2 solar collector 1 has the best economy for solar collector temperatures less than 63 ^{o}C . For higher temperatures solar collector 2 has the best economy.

Efficiency graphs, price calculations for a 4 000 m^2 plant and calculation of production prices have been done for the following variations of the HT-collector.

Cover: Two different glass types were calculated with and without anti reflex treatment.
Convection stop: a calculation without teflon was carried out because this cheaper solar collector might be competitive at lower temperatures.
Absorber: Three different types of absorbers were calculated.
Insulation: Two different types of insulation were calculated.

Table 2.1 shows the example of the calculated efficiency graphs for 3 different absorbers (NIOX and new NIOX from Sunstrip and Tinox) with and without teflon and antireflex treatment. HT-DTI is the collector used in the existing solar collector field from 1996.

Collector	η	k_o	k_1	**Name in fig. 2.1. and 2.2.**
HT-DTI [1)]	0,760	3,500	0,002	HT-DTI
HT-Niox	0,748	2,848	0,006	HT
HT-Niox without teflon	0,757	3,620	0,005	HT-UT
HT-Niox, antireflex	0,771	2,861	0,006	HT-AR
HT-Niox, new	0,756	2,574	0,004	HTSUN
HT-Niox, new without teflon	0,765	3,335	0,004	HTSUN-UT
HT-Niox, new antireflex	0,780	2,585	0,004	HTSUN-AR
HT-Tinox	0,753	3,312	0,004	HTINOX
HT-Tinox, without teflon	0,748	2,585	0,004	HTINOX-UT
HT-Tinox, antireflex	0,771	2,596	0,004	HTINOX-AR

1) measured

Table 2.1. Efficiency graphs for collectors.

And the corresponding calculations of production prices are shown in fig. 2.3. and 2.4. below

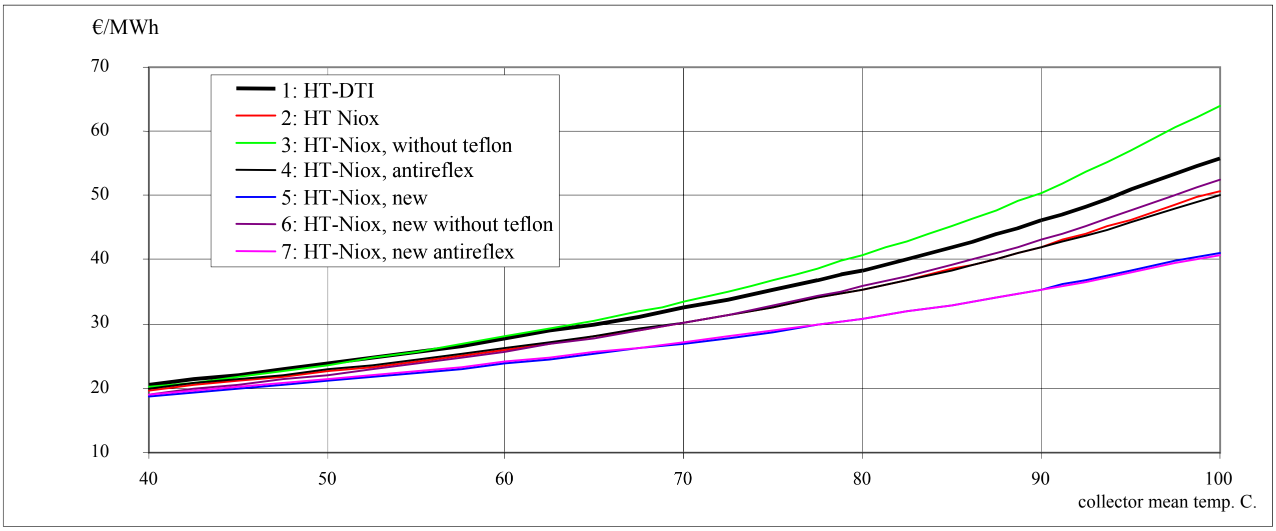


Fig. 2.3. Production price for heat for different collector combinations with Sunstrip absorbers.

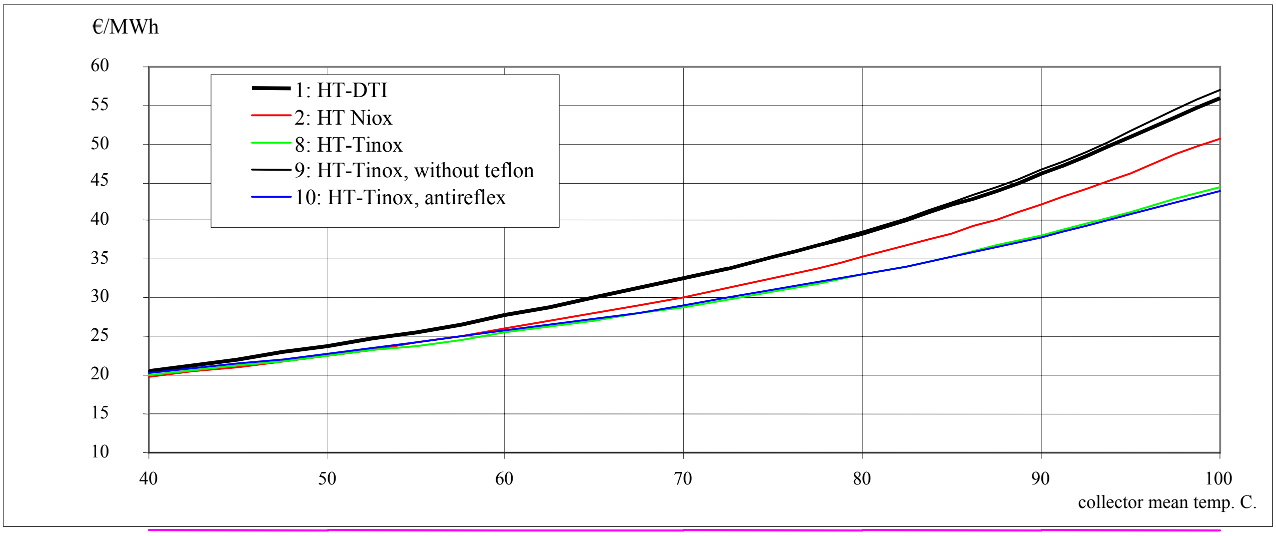


Fig. 2.4. Production price for heat for different collector combinations with Tinox absorbers.

Finally a combination of the best solutions was chosen. The result was that the same combination was the best overall in the temperature range between 40 ^{o}C and 80 ^{o}C and ARCON then built the new HT-Collector.

The new HT-collector included the following changes in the existing ARCON HT-collector:

- antireflex treated Solatex cover
- new Niox absorbers
- Industri 40 insulation

The Danish Technical University (Simon Furbo) measured the efficiency. To compare the results, the HT-collector produced by ARCON 1998-2001 (HT-NIOX) has also been tested under the same conditions.

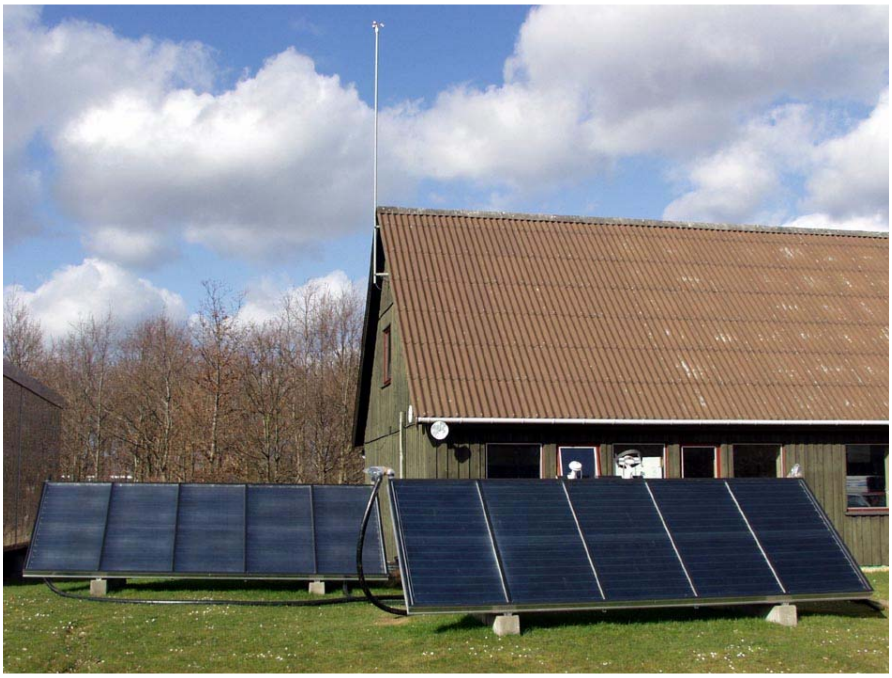


Fig. 2.5. Two ARCON collectors at DTU.

The measured efficiency graph for the new HT-collector was : η_o = 0,81, k_1 = 2,57, k_2 = 0,0079. For the older HT-collector (HT-NIOX) the efficiency graph was measured to: η_o = 0,75, k_1 = 3,07, k_2 = 0,005.
Production costs/MWh for a 4 000 m^2 plant exclusive pipes from solar collectors to heat exchanger, unit with pumps and heat exchanger and storage costs can be seen in fig. 2.6.

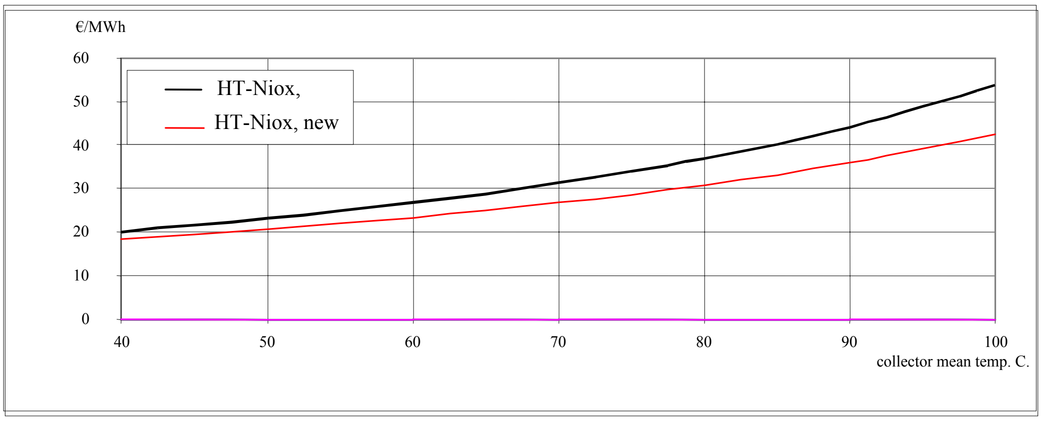
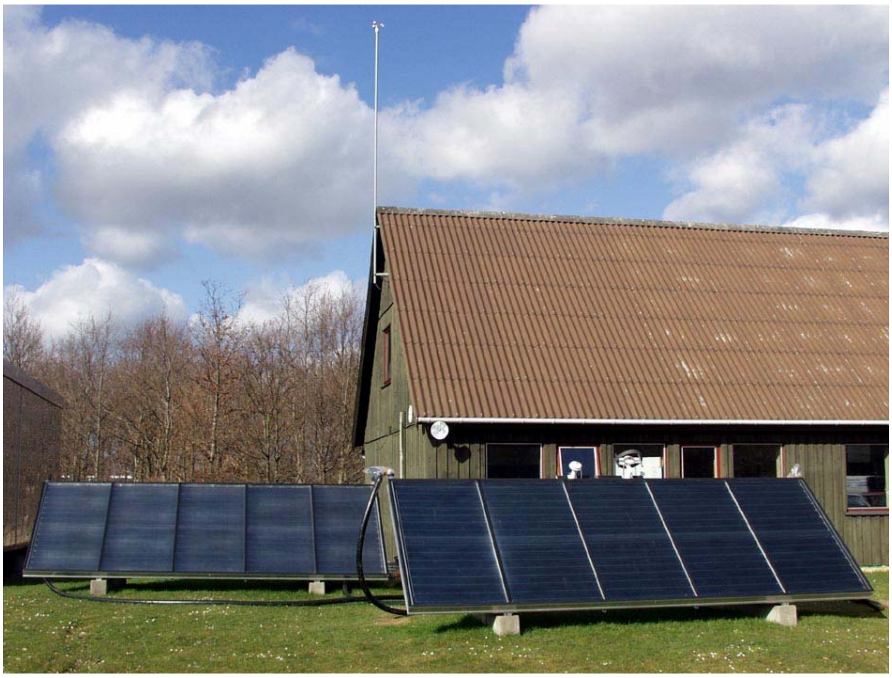


Fig. 2.6. Production prices (€/MWh) for the older and the new ARCON-HT collector

TRNSYS calculations for the new 8 000 m^2 area with HT-collectors in Marstal show a production of 402 kWh/m^2 with the efficiency graph for the older HT-collector (HT-NIOX) and 477 kWh/m^2 with the efficiency graph for the new HT-collector. The production from the new HT-collector is thus calculated at 19% higher. The price for the new collectors is 5% higher than the price for the old collectors. Thus the cost-efficiency was calculated to be 13% higher.



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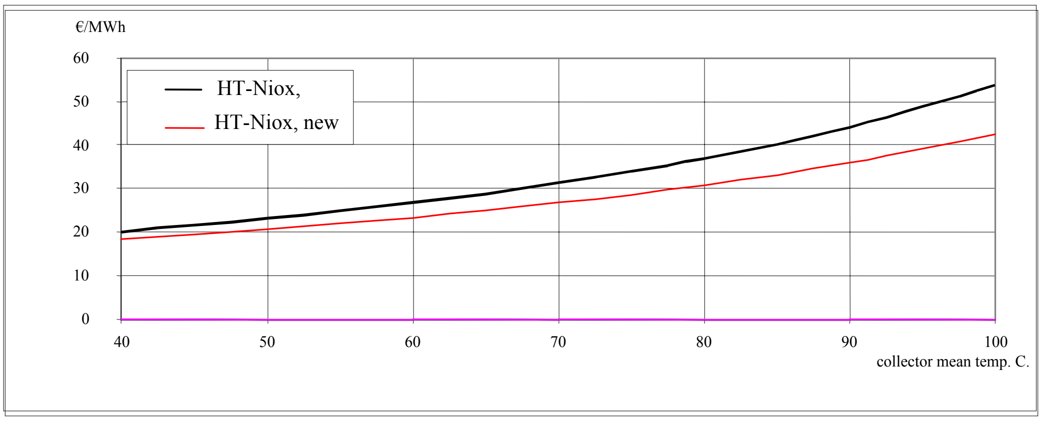

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Finding the most competitive solar collectors.
With the purpose of selecting solar collectors for the demonstration field, prices for 4000 m^2 collector fields along with their data for efficiency calculations were found for the following: (exclusive pipes from solar collectors to heat exchanger, unit with pumps and heat exchanger and storage costs):

- three ground-mounted flat-plate collectors.
- two flat-plate collectors produced as roof-modules.
- four ground mounted collectors produced as evacuated tubes.
- two types of ground-mounted focusing collectors

The data for evacuated tubes and for focusing collectors were determined by Danish Technical University (Alfred Heller) in a project supported by the Danish Energy Agency.

For each type the price of produced heat has been calculated as for the HT-collectors (HT-DTI, see table 2.1.) and the results have been compared in order to find the most competitive producer in each category.

As an example the calculation result for roof modules is shown in fig. 2.7. below.

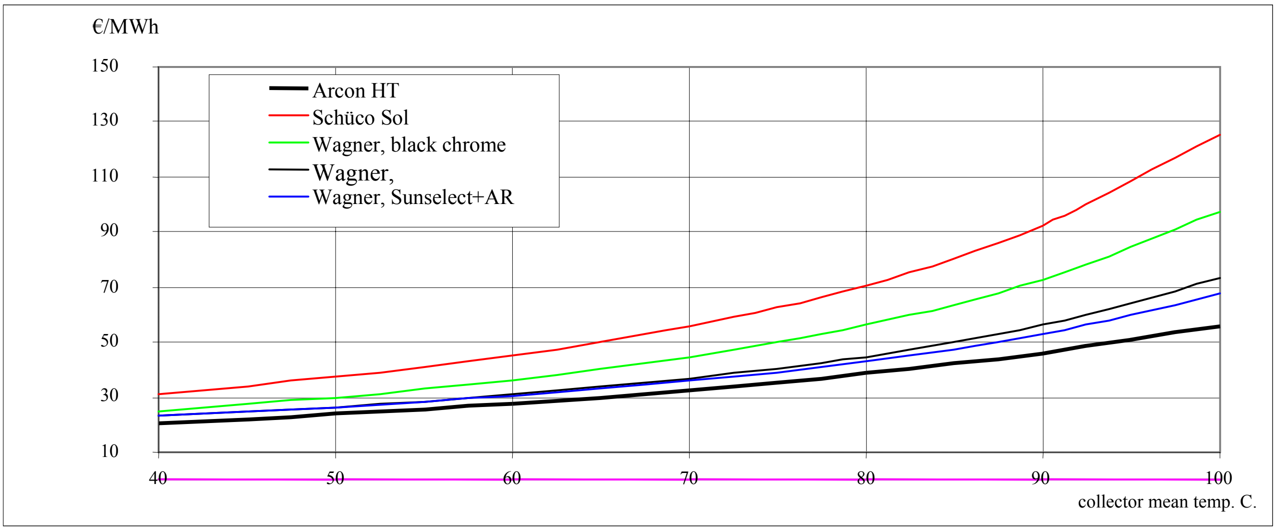


Fig. 2.7. Heat production prices from different roof modules.

It is seen that the existing HT-collector produces heat cheaper or at the same price as the roof module competitors at collector temperatures between 40 °C and 80 °C.

The best collectors in the above mentioned four categories were:
- Flat plate collectors: GJ Teknik, DK
- Roof modules: Wagner SunSelect, antireflex treated, DE
- Evacuated tubes: Thermo Sol (Solamax AST-20MD), UK
- Focusing collectors: IST, US

Design of the total solar collector field
Different ways of making the solar collector field more efficient have been investigated.

- different solar collectors producing at different temperatures.
- using water instead of water/glycol in the solar collectors.
- slope and distance between absorbers.

The idea behind using different collectors is to let them produce at temperatures where they are most efficient. As an example HT-collectors without teflon could produce at collector temperatures between 40 ^oC and 50 ^oC, HT-collectors between 50 ^oC and 70 ^oC and focusing collectors at collector temperatures over 70 ^oC. However, the calculations showed that the new HT-collector is best everywhere in the temperature range. Still the collector field is designed in a way that makes it possible to let focusing collectors and evacuated tubes produce only at high temperatures.

Using water instead of water/glycol in the collector circuit would make it possible to avoid a heat exchanger. Thus the collector temperature could be 5 ^oC lower and the production from the solar collectors higher. However, to avoid freezing in winter the water has to be heated up in periods. This situation has been calculated and the result of the calculation was a minor economical plus by using water, but Marstal Fjernvarme did not want to take the risk of spoiling collectors due to freezing.

Slope of ground mounted solar collectors and distance between the collectors is 40^o and 4,5 meters . To optimise the new collector field TRNSYS calculations has been carried out for combinations of slope (26^o-44^o by steps of 1^o) and row distance (4,0 m - 5,9 m by steps of 0,1 m). The calculations have been carried out including the planned 10 000 m^3 pit heat storage and show an economical optimum at 35^o slope and 5,9 m row distance. The row distance depends on the site price, which is low in Marstal. If we raise the site price to 6 €/m^2 the optimum will be 36^o and 5,4 m. The optimum is very flat, but still the calculation shows that a 2% better production can be reached without extra costs. The chosen row distance in Marstal is 4,5 m because of site limits, and the chosen collector slope is 35^o.

The composition of the solar collector field was decided by the following factors:
- At least 8000 m^2 new ARCON HT solar collectors must be included
- The field must appear as harmonic as possible
- The output must at least be of 8191 MWh/year for the collected field (incl. production from the formerly erected 9043 m^2)
- The price of produced heat must be below 4,5 €cents/MWh

It was decided to place the ARCON area as extension of the present ARCON-field and to distribute the other fields so that smaller fields are purchased of the most expensive solar collectors (IST and TermoSol). Hereafter the complete result of the “jigsaw puzzle” looked like this:

Activity	**Budget (DKK)**	**Cost (DKK)**	**Diff. (DKK)**	**m^2**
Building + 50 m^2		794 000		
Transmission piping		200 000 1)		
Pipes, valves, heat exchangers in building		1 598 905		
Flat solar collectors ARCON GJ-Teknik Pipes in field Liquid		 1 038 9000 1 523 245 730 000 200 000		 8 019 881
Other solar collectors IST Termomax Wagner Pipes in field		 760 000 600 000 258 000 100 000		 211 108 103
Total	15 000 000	17 153 150	2 153 150	9 322

1) Expected

As will be seen, the budget had exceeded its frames by app. 2 mio. DKK, half of which is due to a more expensive building for the technique.
The production of the plant (incl. existing solar collectors) has been calculated at 8 245 MWh/year on the assumption that the new field corresponds to 9 300 m^2 new ARCON solar collectors .

On this background Ramboll (Flemming Ulbjerg) has produced the site plan and system diagram for the total plant..

2.2.3. Supply demands, establishment and start of operation, solar thermal plant.
After negotiating prices for the different types of panels, a number of different options were considered:

1. To operate with only one heat exchanger and then to let the antifreeze first flow through the low temperature panels and after that to let it to the high temperature panels
2. To operate the different types of panels at each one heat exchanger. To monitor the high temperature panels the seriel mode is made at the secondary side.

In order to keep the different types of panels apart and especially to keep the special high-temperature antifreeze in the focusing field separated from the standard antifreeze in the rest, it was decided to install one heat exchanger for each field of panels.

Another advantage of this mode was to make monitoring of the performance easier and to eliminate errors.

In the spring 2003, the new ARCON and the GJ Teknik field was set in operation.
At that time the new heat storage was not build.

This fact did give some surplus heat over the summer, making it necessary to paint the old AR-CON-field with white paste to reduce the performance. (Same type as used in green houses in summer periods)

Over the summer the rest of the plants was set in operation.
The absence of the heat storage needed the focusing panels to be out of operation for long periods.

The start of operation did not give major problems.

It has now become a standard routine to set large plants in operation.
Ordinary problems with air etc. was overcome easily.
Some minor problems did occur concerning the control of the plant and some misunderstanding in the sizing of the speed drives for some of the pumps.

After corrections of these problems the plants have in general been in operation without problems.

The only issue to consider is to replace two small pumps to higher performance.
This issue has to be seen in connection with the strategy for loading the 10.000-m3-heat storage.

2.2.4. Supply demands for the control system

In the development of the first plant in Marstal we did conclude that a new and different mode of operation was needed.
In standard solar systems the flow is normally fixed at a certain level. When operating with fixed flow the outlet temperature from panels will make variations according to irradiation etc.

The conclusion was that the higher solar fraction, the more need for a specific outlet temperature.
The reasons are the following:

- The district-heating network requires a specific flow temperature depending on the demand side. (Space heating and especially hot water preparation.) By operating with a fixed outled temperature from the field / heat exchanger at this level for the supply, the produced solar heat is let strait to the network, and only the surplus flows to the heat storage.
  By operating at lower temperatures than required auxiliary heat is needed at the cost of storing more m^3 at a lower temperature. This is demanding a larger storage.
- To obtain a good stratification in the heat storage, and also in principle a smaller heat storage. (larger temperature difference gives less volume)

Since the plant in Marstal now is enlarged from 15% fraction to 30% fraction the demand for variable flow was even bigger.

For that reason all the new systems are operated by variable flow mode.

The variable flow mode is mainly needed in the summer period. For the mid winter the performance is that low that only pre-heating is taking place in the solar fields. (Constant flow mode is advisable in winter)

In many occasions the advantages and disadvantages by using variable flow mode has been at the agenda.

Our conclusion is that it for the performance of the solar field and heat storage is a growing demand for variable flow the higher solar fraction.
In addition the use of electricity is far lower when operating with variable flow.
Former monitoring results have shown a use of 20 kWh power/MWh heat by constant flow mode.
The according figure for variable flow is less than 4 kWh / MWh heat.

2.2.5. Detailed design of the pit heat storage.

Design criteria.
Apart from the economic criteria mentioned in section 2.2 (< 67 €/m^3 for the actual size, 10 000 m3, < 30 €/m^3 when bigger than 50 000 m^3 - price level 2001) the following design criteria were decided at the start of the design phase:

- Lifetime > 20 years
- Heat loss from cover: < 0.15 W/m2K (corresponding to 300 mm mineral wool)
- No leakage!

Former developments.
In the design phase experiences gained in a.o. the following preceding projects were used:

- Ottrupgaard 1500 m^3 pit water storage. (1995)
- Floating Lid Constructions for Pit Water Storage. Phase II. (1998)
- Floating Lid Constructions for Pit Water Storage. Phase III. (2000)
- 3 500 m^3 Gravel Pit Storage. (Marstal). (1999)

all financed by the Danish Energy Agency.

In Ottrupgaard a clay liner backed by an EPDM-membrane was used for the pit. The floating lid was build by prefabricated wall elements for cold stores consisting of PUR foam between corrugated steel plates. The design proved feasible, but the construction phase involved so many unexpected difficulties and expenses that it was obvious that this design could not meet the economic criteria.

In the Floating Lid, Phase II, project four different designs for a floating lid were suggested:

1. Full length floating modules app. 6 m width. PP liner with mineral wool. (76 €/m^2)
   - Modules build on-site from one end, gradually floating on the surface of the pit.
2. Further development of the Ottrupgaard lid. Welded joints between the lower stainless steel plates of the sandwich modules. (194 €/m^2)
   - Safe, but very expensive design.
3. Modules 20 * 20 m. HDPE liner with EPS insulation. (90 €/m^2)
   - Many cold bridges. Difficult design of border.
4. Modules 2 * 1 m. PP liner with mineral wool insulation. Modules topped by unbroken mineral wool layer. (129 €/m^2)
   - Complicated construction. Rather expensive.

In the Floating Lid, Phase III, project further development and evaluation of the four designs were carried out. This phase concluded the following three designs:

1. Solution 1. of the former phase. A full-scale test was made of the construction in a test pool. On this basis a new evaluation of the costs gave a result of 57 €/m^2.
2. One continuous liner floating on the surface. Made by welding from lengths of PP or PB (width app 6 m). Bulk insulation (Leca). Cost estimation: 47 – 64 €/m^2.
3. One continuous liner made of stainless steel. Welded in situ. Insulation mineral wool. Cost estimate: 95 – 150 €/m^2.

The Marstal Gravel Pit Storage used welded PP liners for bottom, sides and top. At the bottom and the sides a secondary liner consisting of bentonite backed the liner. The top was insulated by 100 mm bulk insulation (Leca) and 150 mm mineral wool. Heat is stored in the wet gravel and is brought to and taken away from by a distributed heat exchanger consisting of 5 400 m PEX tubes.

This storage has been successful regarding the liners, as no leakage has been detected, but the storage function has been disappointing due to two problems: A. An unexpected large heat loss through the sides caused by moving ground water. B. Less efficient heat transfer than expected by the PEX tubes. As a result the storage is used as a low-temperature storage (below 55 ^oC) connected to a heat pump.

At the start of the present project the following conclusions were made on the above background:

- Water filled pit (contrary to gravel)
- Floating cover with either full-length modules (solution 1 above) or one continuous plastic liner welded in situ (solution 2 above).
- Bottom and sides: One layer plastic liner.

A number of problems still had to be solved, as described below:

1. Choice of liner(s) for bottom, sides and lid.
2. Temperature expansion of plastic liners.
3. Design of fixtures for the top liner
4. Choice of insulation material(s) for the lid.
5. Eventual condensation in the lid.

Choice of liner(s) for bottom, sides and lid.
Simultaneously with the mentioned test- and evaluation projects accelerated test on various plastic liners were made by the Technological Institute of Denmark (financed by the Energy Agency).

Different liners were tested at 100, 107 and 115 ^oC with water at one side and air at the other.
Lifetime was defined as the time, where tensile strength was reduced to 50% of the original value.

Based on these results the equivalent lifetime for the actual conditions (temperatures between 35 ^oC in the winter and 80 ^oC in the summer) could be calculated using the Arrhenius equation.

The results for the most promising two liners are shown below:

	Lifetime	
Temperature ^{o}C	HDPE 1	HDPE 2
100	400 days	530 days
107	200 days	330 days
115	120 days	180 days
Equivalent (35 – 80)	22.6 years	24.3 years

Both HDPE liners had 2.5 mm thickness and represented two different German suppliers.

The 1.6 mm PP liner used in the gravel pit storage showed shorter lifetime than expected (less than 10 years at the design temperatures for the pit water storage). This is part of the reason why this storage is now operated at temperatures below 55 ^{o}C.

Theoretically other liners with good high temperature properties could be developed like PEX or different types of compound materials, but in cooperation with ITW, Stuttgart, it was concluded that the only available liner with the wanted durability was 2.5 mm HDPE.

The XR-5 woven composite polyester liner from Seaman Corporation, which has been used for solar pond experiments in America, was disqualified on theoretical considerations based on information on the composition and an accelerated test at 115 ^{o}C. The temperatures used in the recorded experiments were 10 – 15 ^{o}C lower than the design temperatures for the storage in Marstal.
The 2.5 mm HDPE is easy to weld but – because of the thickness – difficult to fold and to bend around sharp edges. This caused design solution 1 unpractical and thus caused the choice of solution 2: one continuous liner, welded in situ.

Temperature expansion of plastic liners.
HDPE has a relatively high temperature expansion coefficient ($12 * 10^{-5} K^{-1}$). This causes expansions of the liner of nearly 1% from winter to summer.

The situation at the border of the lid is critical in this respect. As the length and the width of the lid is app. 50 m an expansion of 50 cm has to be coped with.

In order to get experience with the chosen liner regarding temperature expansion e.g. in fixed edge situations an experiment was carried out.

A 1*2 m piece of liner including a welding was fixed in a steel frame and heated in water from app. 10 ^{o}C to app. 80 ^{o}C. A photo of the result is shown below:

Fig. 2.8. Expansion experiment. 2.5 mm HDPE. 70 °C.

The expansion took place in a slow and uniform way without formation of sharp edges. The liner returned perfectly to original shape when cooled. This was also true for the welding (not seen at the photo).

It was found that the necessary force to make the bigger 'hills' shown at the photo level out to a number of smaller hills was app. 100 N. As the weight of the lid is app. 20 kg/m^2 it can be concluded that the typical hills formed in a situation where the liner is fixed at the edges and trapped between a flat insulation and the water surface will be about 0.5 m in diameter and have a maximum height of about 5 cm. This will add an extra gradual lift of the lid of 2-3 cm compared to the 3 cm lift caused by the expansion of the water, when the average temperature increases from app. 35 °C to app. 75 °C. These potential annual movements will be minimised by manually adding or subtracting app. 100 m^3 of water. As this is done to the bottom of the pit it will cause a heat loss of less than 4 MWh/year.

The fixing of the liner at the edge was in the final design achieved by placing a steel grid on top of the liner and fixing the liner to the grid at the edges. The steel grid also provided a firm floor for the insulation of the lid.

This design detail is illustrated by the drawing below:

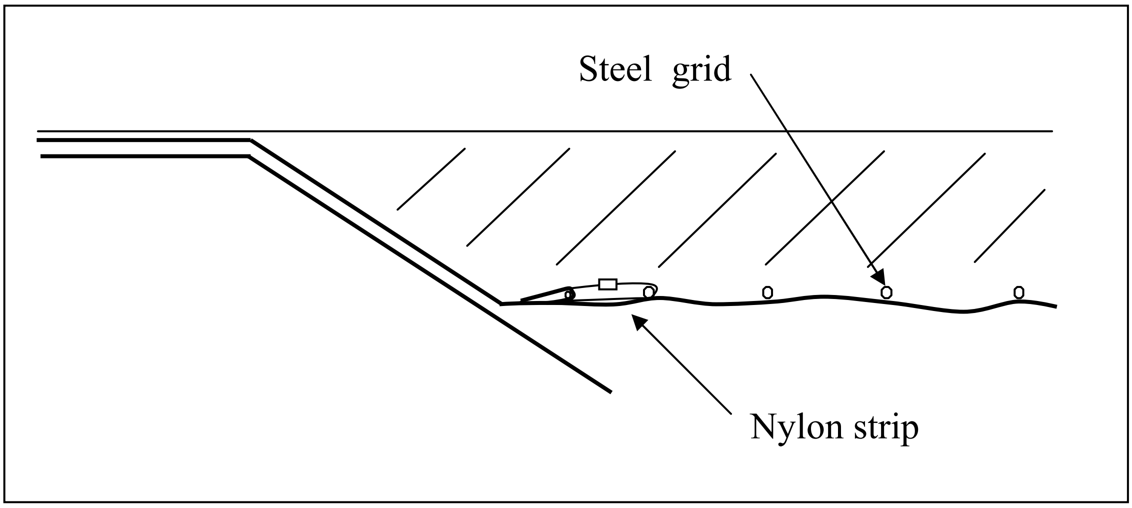


Fig. 2.9. *Steel grid to counteract expansion.*

Design of fixtures for the top liner
The drawing below shows a cross section of the edge for the final design. The choice of insulation material and vapour barrier is described in the following sections.

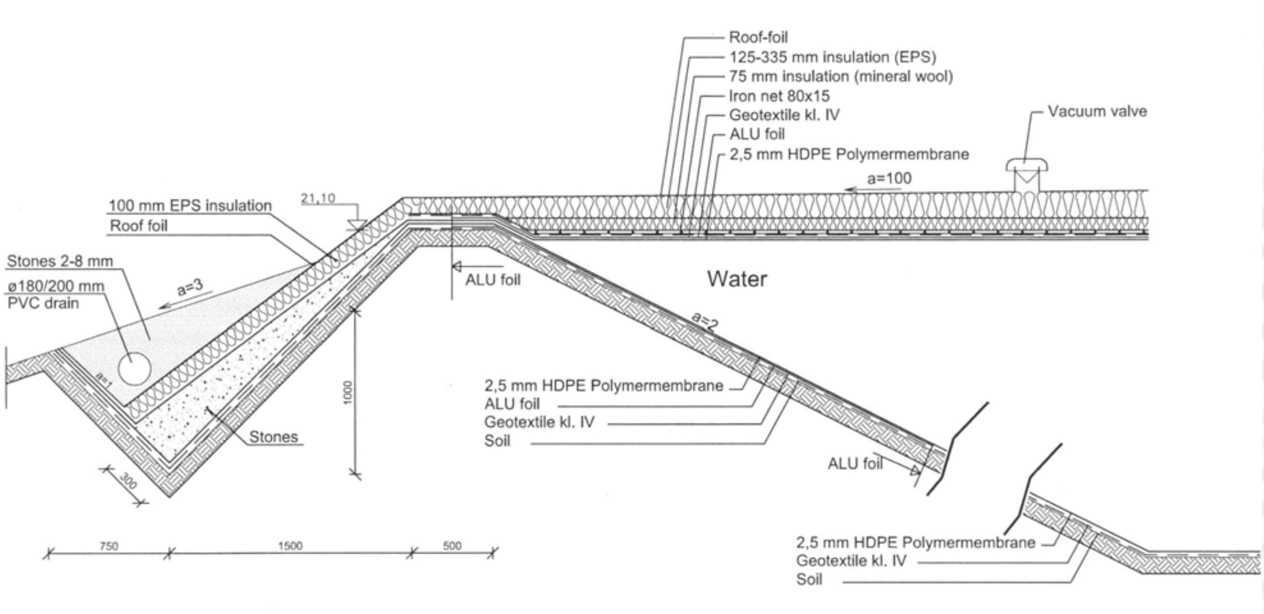


Fig. 2.10. Cross section of the edge of the pit storage.

The cross section drawing emphasises the design details for the edge. It should be noted that the top insulation increases toward the center of the lid and that the part of the bottom is shown ‘too early’ for illustrative reasons. In reality the depth of the pit is not 2 m as shown but 6.5 m.

The design is explained ‘bottom-up’:

- The original soil must be machined carefully and all visible stones with sharp edges above 2-3 cm length must be removed.
- To protect the side/bottom liner a heavy geotextile is used.
- The side/bottom liner is mounted in lengths of 6 m width. It is welded in situ. For long regular joints double weldings are made by self-propelling equipment. The volume between the weldings is tested for leakages by compressed air. In corners etc. extrusion welding is used. Always as double weldings. 100% controlled by high tension spark equipment.
- One by one the length of liner is fixed in the locking ditch by the lower volume of stones.
- On the top part of the side an alu-foil is placed between the geotextile and the liner. This protects the soil from condensation caused by the small amount of vapour passing through the liner at high temperatures. (see section concerning vapour and condensation).
- Now water is added.
- The bottom liner of the lid is made by in situ welding next to one end of the pit. It is gradually floated as it is produced.
- When the liner is complete the side insulation is placed and insulation and liner is fixed in the ditch by adding part of the top volume of stones.
- Now the lid can be build from one end by adding the following layers one by one: Alu-foil, geotextile, iron grid, mineral wool, EPS and roof foil. The thickness of the insulation increases from 200 mm at the edge to 410 mm at the center of the lid. This creates a 1:100 slope to counteract the forming of rainwater pits.
- As this process proceeds the roof foil is finally fixed in the ditch by adding the rest of the stones. In case of strong winds the roof foil will be sucked to the lid by a vacuum formed by vacuum valves (standard roof design).

Not shown in the drawing is the 1 000 mm diameter manhole at the center of the lid, the connecting tubes (see sec. 2.2.6) and the various transducers for the control and monitoring system (sec. 2.2.7).

Choice of insulation material(s) for the lid.

In cooperation with ITW, Stuttgart, a number of possible insulation materials for the lid were evaluated. Some of them were:

	Conductivity W/mK	Price Euro/m3
Mineral wool	0,05	250 in lid
EPS	0,05	170 in lid
Perlite	0,05	60 at Aeroe
Leca	0,07	60 at Aeroe
Poraver	0,07	150 at border

Mineral wool has low conductivity and is available in many shapes and with different carrying capacities. It can be supplied with defined slopes to fasciliate the forming of a suitable slope for the roof foil. The only problem with this material is the price. In the table an estimate for the building-in of the material is included.

EPS (expanded polyester) has similar properties, but has a temperature limit of app. 70 ^{o}C for long time exposures.

The following three materials are all bulk materials consisting of small spheres in the range of 2 – 10 mm. Perlite is made from volcanic material, Leca from a special clay and Poraver from glass waste. Particularly Perlite has an interesting relation between price and conductivity, but the necessary measures for ensuring the shape of the roof foil was found to be too expensive. One possibility would be to add the Perlite in the form of big 'mattresses'. It would still be necessary to use e.g. plywood plates between the insulation and the roof foil. This method has a disadvantage, which also applies for the above-described methods for mineral wool and EPS: For bigger storages it will result in insulation thickness at the centre of the lid, which are uneconomical. A rafter design might have to be considered. If rafters carry the roof foil anyway the use of Perlite becomes very relevant.

In the present project the use of the well-known materials mineral wool and EPS was decided. Mineral wool for the lower 75 mm and EPS for the rest to keep the temperature of the EPS well below the recommended 70 ^{o}C.

Eventual condensation in the lid.
To gain understanding of the nature of the condensation problem the vapour transport situation for a lid with 450 mm of mineral wool insulation (the centre of the actual lid) was considered. A simple multilayer method was used. A temperature difference of 90 ^{o}C (from 90 ^{o}C at the water surface to ambient 0^{o}C) and the following layers: 2.5 mm HDPE, 9 * 50 mm mineral wool plus roof foil was assumed.

The vapour influx through the liner depends on the vapour resistance (Z-value) and the difference between vapour pressure on the two sides.

The Z-value was estimated from data given by the supplier.

The permeance of a 1.5 mm HDPE was given as 8.2 E-14 kg/m2 Pa s (at 50 % humidity, 23 ^{o}C).

This gives app. Z = 10 000 Gpa s m^2/kg for a 2.5 mm liner (at 23 ^{o}C).

Søren Pedersen, Danish Institute of Tech., suggest that this value will decrease app. by a factor 2 for each 10 ^{o}C the material is heated. He has measured vapour resistance for PP at temperatures in the relevant range, which confirm this assumption, but not HDPE.

Using this relationship we get Z = 96 Gpa s m^2/kg at 90 ^{o}C.

The vapour pressure at the dry side of the liner can be considered low (app. 2 kPa) as the bottleneck for the vapour transport is not in the hot part of the insulation but in the cold part.
As the partial pressure for steam at 90 ^{o}C is app. 70 kPa the steam influx can be found to be

S,in = (70 – 2) kPa / 96 Gpa s m^2/kg = 0.7 E-6 kg/s m^2

This value can now be compared to the ventilation at the top of the lid.

The situation is calculated for an ambient temperature of 0 °C. The ventilation through the valves of the vacuum roof is considered sufficient to prevent condensation on the 'hot' side of the roof liner. At the surface of the top insulation the maximum value of the vapour pressure is therefore the condensation pressure: 0.6 kPa. This assumption requires sufficient horizontal ventilation between the top insulation and the roof liner. This has to be taken into account in an eventual design.

The insulation is assumed to consist of 9 layers of 50 mm = 450 mm mineral wool with a Z value of 0,35 Gpa s m^2/kg for each layer.

The temperature at the 'hot' side of the top layer is 9 °C., which correspond to a maximum vapour pressure of 1.14 kPa. The vapour transport through this layer in the critical situation where condensation might occur is:

S,out = (1.14 – 0.6) kPa/ 0.35 Gpa s m^2/kg = 1.5 E-6 kg/s m^2

This means that condensation theoretically should not occur as the maximum vapour output capacity it about twice the input. There are however a number of uncertainties in this calculation:

- first of all the temperature dependence of the vapour resistance of the HDPE has not been measured directly. An error in the range of a factor 10 can not be ruled out.
- secondly it is assumed that the vapour influx through the HDPE is the only source of water in the lid. The max. total vapour output in the winter corresponds to app. 350 kg pr day. This shows that a very small leakage can spoil the balance.

The above conclusion is valid for other insulation materials with low vapour resistance like Perlite, Poraver and Leca, as the vapour resistance of these materials is similar or lower than the value of mineral wool. For materials with much higher vapour resistance like expanded or extruded polyesterol (e.g. 30 Gpa s m^2/kg for 100 mm) the need for a vapour barrier is obvious.

For these reasons a vapour barrier with a guaranteed resistance of e.g. more that 10.000 Gpa s m^2/kg at 90 °C placed at top of the liner was needed.

Barriers incorporating aluminium foil only can secure this.

A common type of vapour barrier consisting of PP foil, a thin layer of aluminium (10 μm?) sprayed on this foil, a grid of glass fibre (12 mm), and a PE foil was tested by boiling it for a few hours at 100 °C. It shrinked app. 4 % and got out of shape.

With the assistance of Stutgart University an alternative barrier was identified, produced by the company Alujet. This barrier is made for high temperature applications like Saunas.
It consists of the following layers: Al foil (9 μm) Polyester (23 μm) Al foil, Polyester, Al foil. The total of 27 μ m aluminium formed by three actual aluminium foils secures very high vapour resistance (app. 20 E6 Gpa s m^2/kg). The fact that the polyester is protected from evaporation and from oxygen indicates that it can be used at high temperatures. The price is 1.86 Euro/m^2 delivered in

Denmark. One problem is the joining, as it can not be supplied in width more than 1 562 mm. It can however be joined by a double sided adhesive tape, which costs 0.28 Euro/m.

A test similar to the one described above shoved almost no effect of boiling the barrier at 100 ^{o}C for two hours, and the alujet barrier was chosen.

2.2.6. Tender and establishment of the pit heat storage.

Tender.

A number of companies did give proposals for establishing the heat storeage.

Contract	Company	Tender, € excl. VAT
Excavation	Ollerup Maskinstation	164.500,-
	Helge E. Andersen	187.200,-
	Vindeballe Entreprenørforret-ning	180.200,-
	Pilegaardenes Maskinstation	153.000,- x)
Liners and roof	Jakobsen & Blindkilde	495.600,-
	GG Construction	458.700,- x)
In- and outlet pipes.	GJ Teknik	22.000,- x)
Heat exchanger station	GJ Teknik	78.600,-
Control and monitoring	INVENSYS	62.400,-

note: given the contract: x)

Especially the proposal from GG Construction was of interest because of its proposal for alternative solutions.

1. to change from mineral wool to EPS insulation gave huge reduction in the price.
2. to change the roofing to a vacuum type roof, where the roof-liner was not to be fixed to the underlaying iron grid.

After negotiating and finding modifications the solution for the roof was a mix of mineral wool and EPS.
The vacuum-roof system was chosen as well.

Excavation
The work did start May 13. 2003 and was finished by the end of June same year.
from the survey of the ground secondary layers of ground water was found.
A combination of layers of sand and clay was found as well.
To make it possible to keep the pit free of ground water a larger project for reducing the level of the ground water was set up.
This part of the project was without problems.
The capacity was sufficient and placed in good positions relating to the different layers of clay.

Fig 2.11. The nearly finished excavation, June 2003.

Sideliner
The technology applied for the sideliner is well known from erecting liners in landfills.

The work to place, weld etc. the sideliner did start after July 4th 2003 and was finished July 18 th 2003.

This period did include time to solve the problem of the sliding liner.

We have faced two mayor problems.

1. Insufficient locking of the liner at the top.
   This problem was an ordinary misunderstanding concerning responsibility for the liner / excavation.
   The problem was related to too few sandbags to keep the liner in place until the water filling was finished. After pulling the liner in place and filling more sandbags in the trench, no more problems occurred in this respect.

2. next problem faced was when filling with water. The sunny conditions did heat up the liner not covered by water. The heating of the liner did of course enlarge the line giving characteristic folds right over the surface of the water.
   It appeared not to be a mayor problem either. As the level of water did rise the folds did more or less disappear. At two places there are still folds. They are not considered to be a problem for the future.

Fig. 2.12. Foldings during filling up.

In- and outlet.
The design of the in- and outlet of water was complex. The solution got to be 2 ø 500 mm HDPE pipes inserted in the side liner.
The sideliner is sloped 1:2 but the in- and outlet pipes are level, giving difficult angels to weld, tighten etc.
After filling the storage a major leakage was actually at this weak point.
It was easy to locate and relatively easy to repair.

The supply pipes (pre-insulated) from the heat exchanger station was fitted in the above mentioned HDPE pipes.

Fig. 2.13. In- and outlet.

Waterfilling
The authorities did allow to soften the water, but not to treat it in any other way.
This is because of the reserves of ground water for drinking purposes in the area.

The capacity of the water supply did have limits as well. The filling was planned to take one month, which also was the spent time for the job.

Apart from the problems with the sideliner, no problems were seen in this part of the process.

Topliner.
How to place a 2,5 mm HDPE liner on 2500 m^2 of water ?

GG Construction did have the answer:

To weld the liner beside the pit and then to draw it like a curtain over the water. !
One tractor in each corner and a closed tube at the edge to keep the edge of the liner above the water was all needed.

It took less than 3 days of work to weld and to cover the water surface.

Fig. 2.14. The top-liner nearly drawn over the water.

Roof.
To make the rest of the roof (insulation etc.) was very sensitive to the weather conditions.
Wind as well as rain can damage the work.

The main part of the time the weather conditions were OK. A short stop was necessary because of wind as well as rain.
The rain did give some moisture in the construction, that now is evaporating from the construction.
An opening of the lid in 2004 did show that the lower layers are dry, but the top is still humid. The development of the humidity will of course be followed closely for the future.

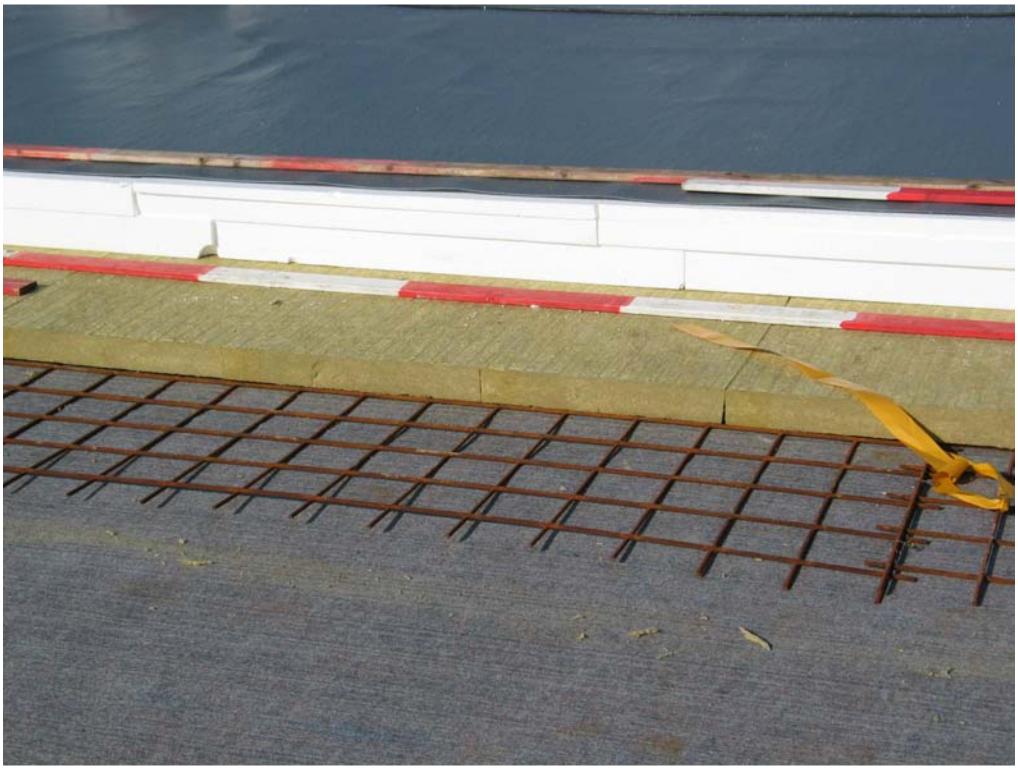


Fig. 2.15. The construction of the roof: geo-textile, iron grid, mineral wool, EPS insulation and roof foil.

Running in/start of operation.
The heat storage was finished after the sunny season and thus not in operation before spring 2004.

One topic of certain interest was how to keep the floating lid at a specific level. ?

The entire construction is made from the assumption that the lid does not move up and down by changes of water temperatures.
The idea is to drain and to refill by water as the demand for it varies.

A special device (ultra sonic distance) is fitted to control the level of the water. It is placed on top of the water-inlet disc and is measuring the distance to the water surface.

The drain and refill does have to be made manually by opening valves etc.
Experiences have shown so far that only refilling is needed, because of penetration through the liner and maybe a very small leakage. (less than 1 m^3 pr day).

In spring 2004 the loading of the heat was set in operation.
After commissioning flow, pumps etc. the loading and offloading is now in automatic operation mode.

For every day is chosen a certain period where one of the two options is in operation.
So far we have not found a full automatic mode for this. The reasons are mainly due to the fact that a lot of observations actually forms the decision to load or offload. Weather forecast is one of the observations needed.

2.2.7. Monitoring System

The Marstal Solar Heating Plant is equipped with an extensive monitoring system. In the hydraulic system temperature sensors, flow meters, pressure sensors etc. as well as separate heat meters are installed in all relevant places. Figure 1 shows a scheme of the hydraulic system and the positions of the monitoring sensors in this part. In the solar collector fields additional temperature sensors are installed at the outlet of every single collector row. In the new Arcon field one collector row is equipped with additional temperature sensors between the single collectors.

The heat stores are also occupied with numerous monitoring sensors. The new 10 000 m^3 water filled pit heat store is equipped with temperature sensors in- and outside the storage volume, heat flux sensors in the top layer as well as a moisture sensor and temperature sensors within the floating cover to get information about the long-term heat and steam transport processes through the wall constructions. The positions of the different sensors in and around the heat store can be seen in figure 2.

Climatic data is recorded by a couple of Pyranometers in the different collector field orientations, wind speed and wind orientation sensors as well as an ambient temperature sensor. The data is recorded, processed and stored by the control system of the plant in combination with a database.

With the information from the monitoring system, contributions of the single heat producers like the different collector fields, boilers etc., and the total heat balance of the district heating system can be calculated. Also the operation and e.g. the hydraulic adjustment of the single collector rows can be observed.

The measurements from inside and outside the two seasonal heat stores deliver valuable information about the long-time behaviour and the efficiency of these components that are still under development. Seasonal heat stores e.g. have higher heat losses in the first three to five years of operation because the surrounding ground has to be heated up to steady-state operating conditions. The temperatures from the surrounding ground give information about this effect and about the influence of possible overlaying effects like groundwater movements.

The collector fields added within the SUNSTORE2 project period started operating end of February 2003. The monitoring equipment was first connected in September the same year. From January to mid of March 2004 a problem with the monitoring database server prevented a recording of data.

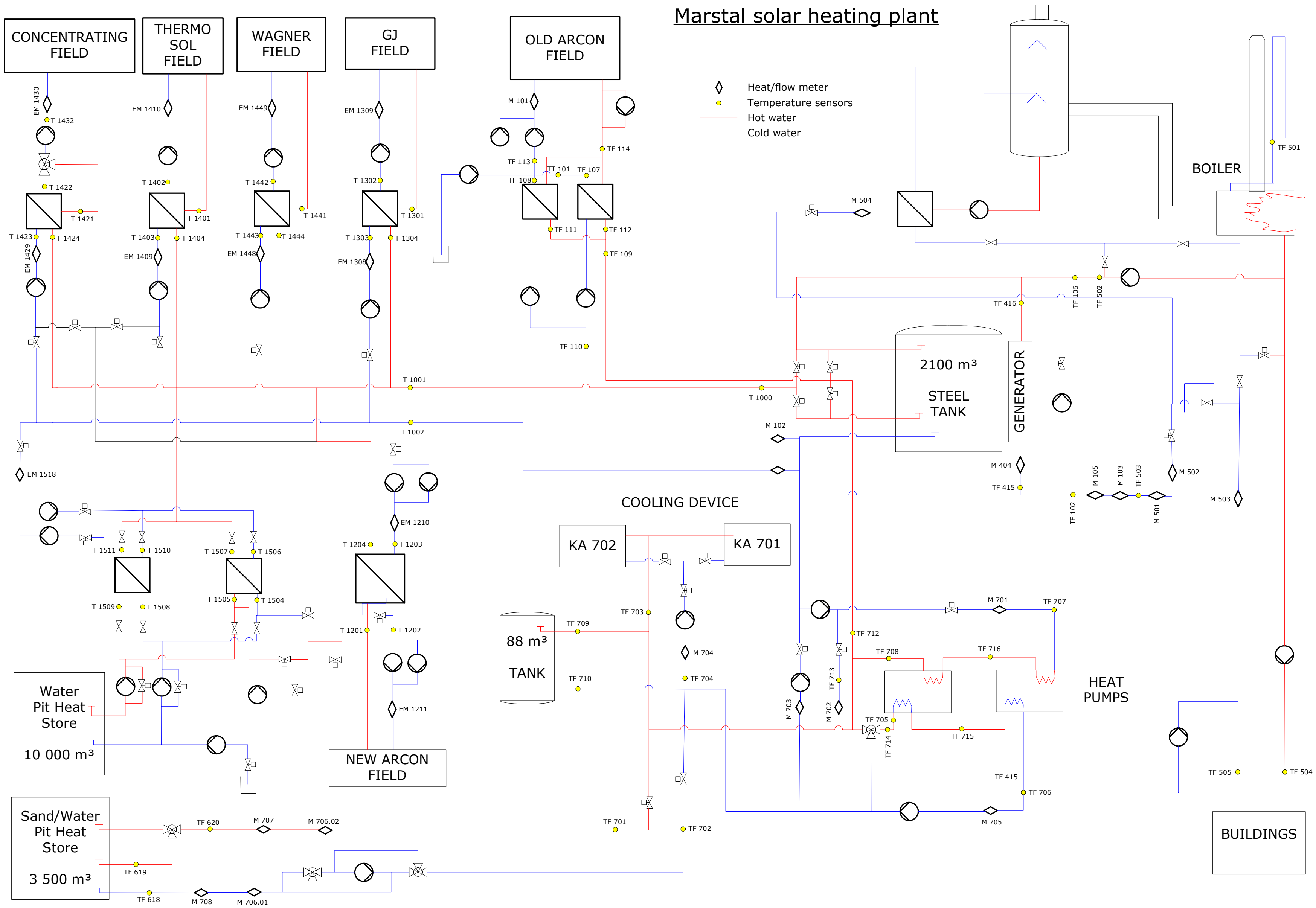


Fig. 2.16: Hydraulic plan of the Marstal solar heating plant with monitoring sensor positions

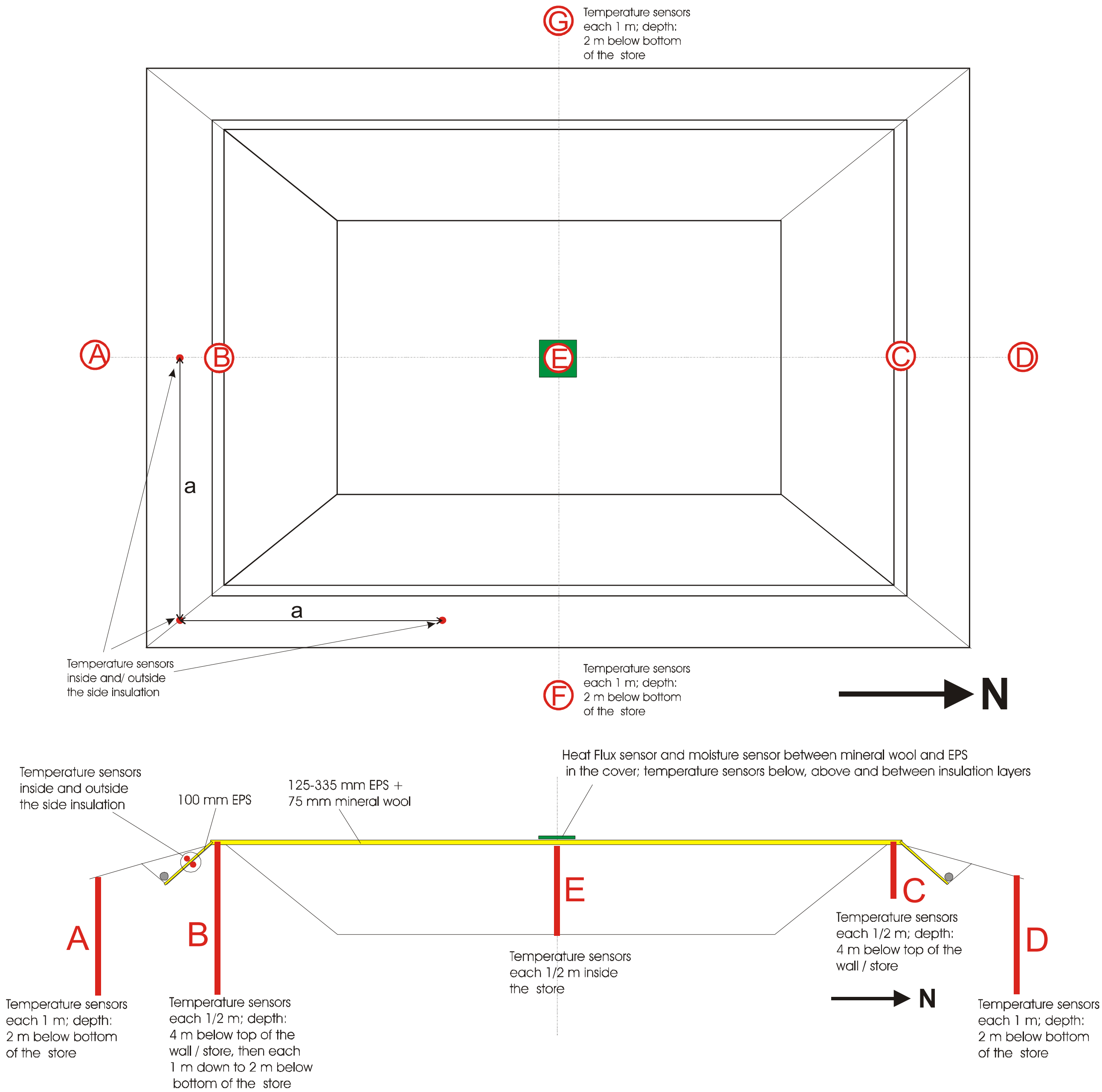


Fig. 2.17: Monitoring sensors in and around the 10 000 m³ seasonal pit heat store

Heat Balance

Figure 2.18 shows the system heat balance from October 2003 to September 2004. During the summer months 2004 nearly the whole heat demand was covered by solar energy. Besides, 773 MWh of solar energy were charged into the new pit heat store. The solar heat produced by the collector fields between March and September 2004 was 6 465 MWh. The heat delivered to the city within this time period was 8 478 MWh, 2 715 MWh were provided by the oil boilers.

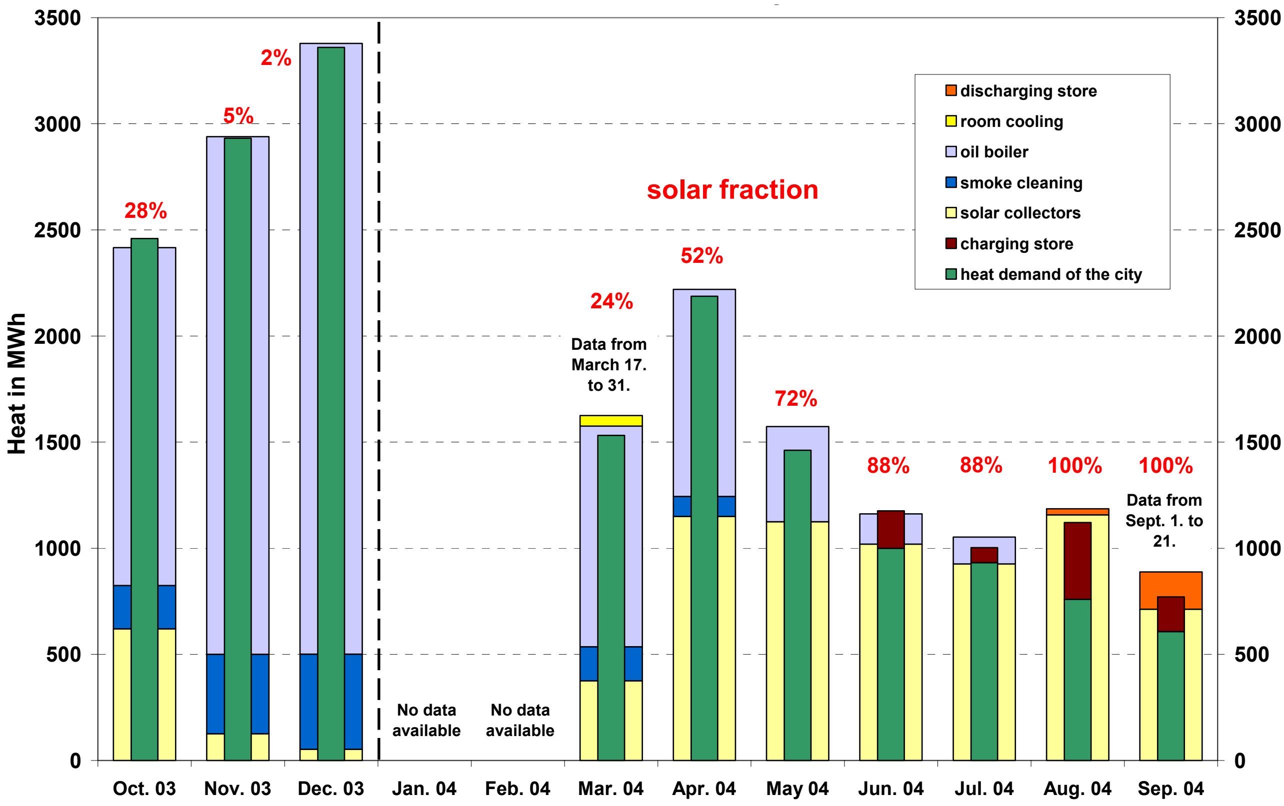


Fig. 2.18: System heat balance from October 2003 to September 2004 according to heat meter data

Solar Collector Fields

Table 1 gives an overview of the different collector fields and their heat production during summer 2004. The monthly heat production of the single collector fields can be seen in figures 2.19 and 2.20 The main solar heat delivery comes from the two Arcon fields because they have by far the biggest area (figure 2.19). The highest specific solar gains were achieved by the Thermosol vacuum tube collectors followed by the GJ, the new Arcon and the Wagner collector fields (figure 2.20).
Table 1: Collector field heat production between March and September 2004

Field	collector type	area [m²]	slope [degrees]	specific heat production [kWh/m²]	total heat production [MWh]
Arcon old	flat plate	9043	40	337	3049
Arcon new	flat plate	8019	35	369	2960
GJ	flat plate	881	35	389	343
IST	parabolic trough	211	tracked	142	30
Thermosol	vacuum tube	108	40	429	46
Wagner	flat plate (Solar Roof)	103	32	358	37
Total:		**18365**		**352***	**6465**

*: mean value weighted by area

It can be observed that the heat production of the Wagner Solar Roof collector is as high as the one from the GJ collector in the summer month, but slightly less than all the other flat plate collectors during the rest of the year. This is because the slope of the Wagner field (31°) is 5-10° less than that of the other fields (35-40°).

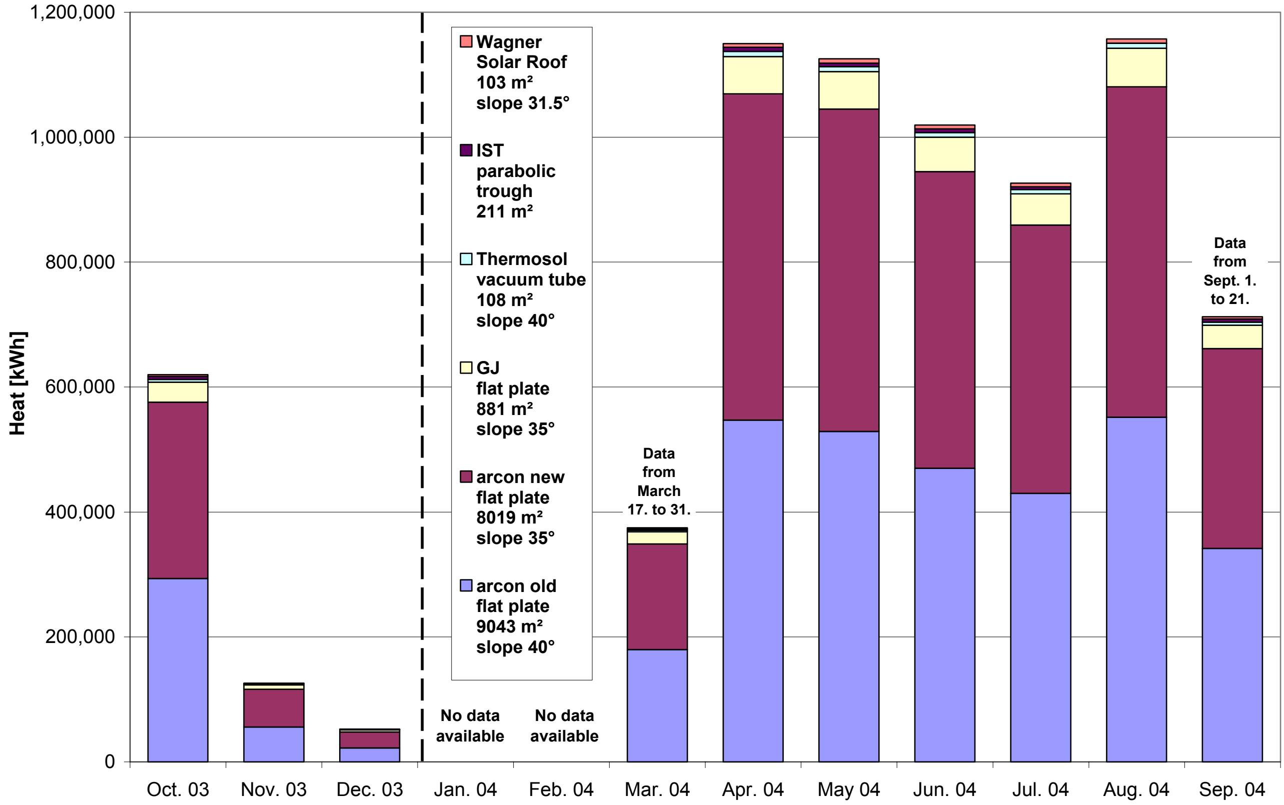


Fig. 2.19: Monthly solar heat production

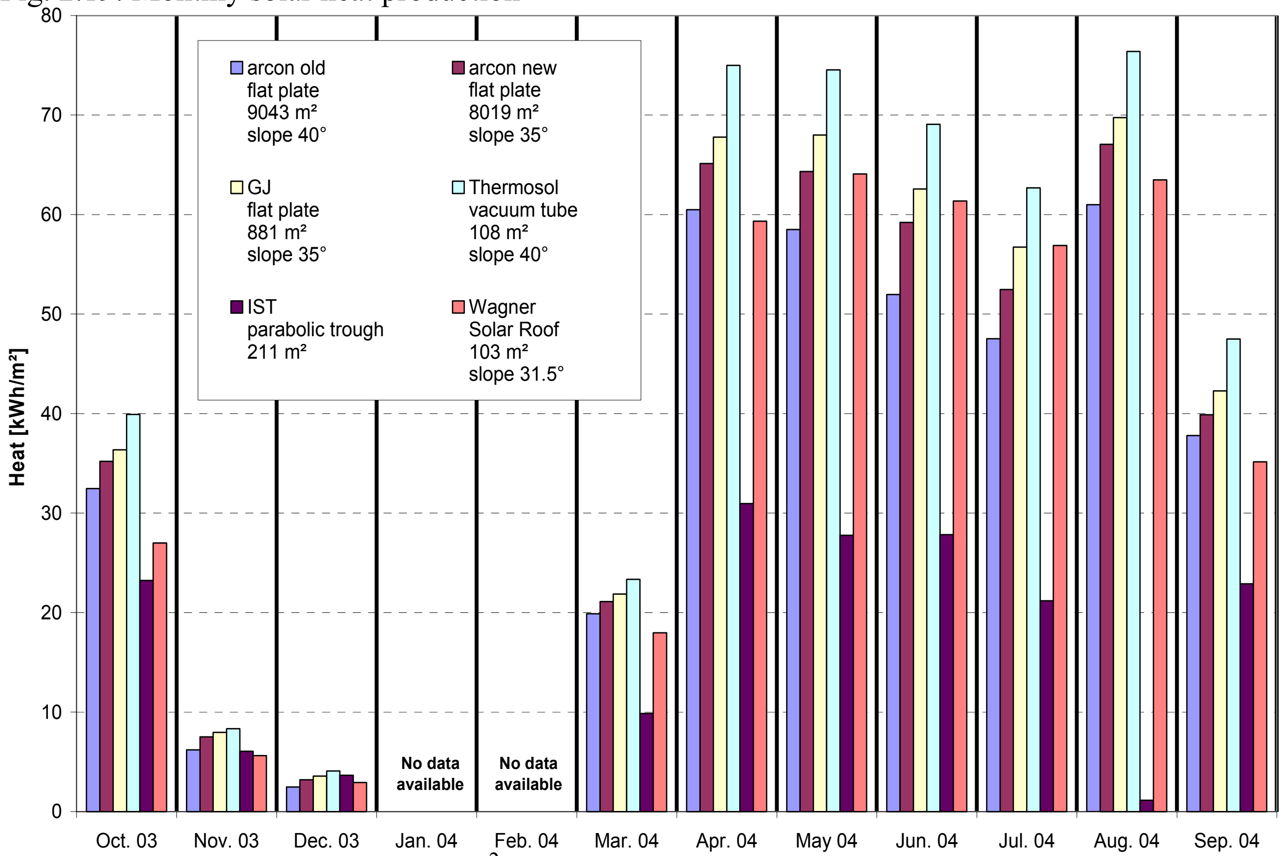


Fig. 2.20: Solar heat production per m^2 collector area.

The IST parabolic trough collectors had the lowest heat production. The main reason for this is shown in figure 2.21: there is a high diffuse fraction in the solar irradiation of up to 50 %. Diffuse irradiation can hardly be used by this type of solar collector because of the focusing system. Another reason for reduced heat production of this type of collector is often an imprecise adjustment of the tracking system. This however has been checked frequently in Marstal and can be excluded as a reason.

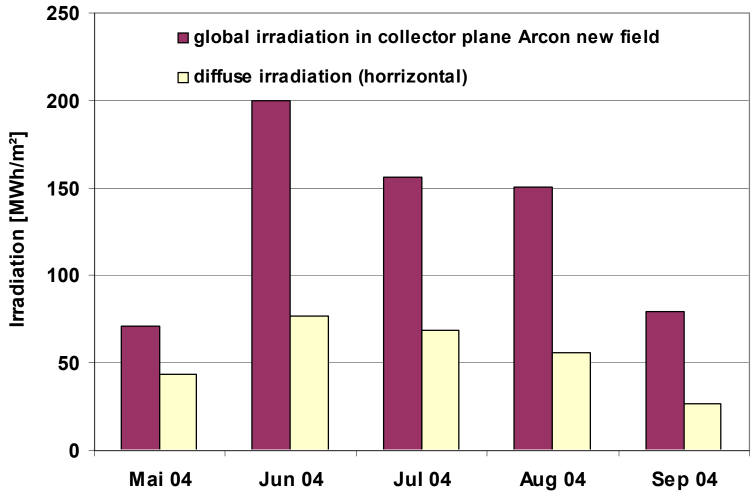


Fig. 2.21: Global and diffuse irradiation (global: tilted 35°, orientation south; diffuse: horizontal)

In figure 2.22 the temperature distribution within the new Arcon field is exemplarily presented. Despite the size of the field (high thermal capacity) and the slow reaction time to operational changes, the control system manages to meet an almost constant production temperature during the whole day.

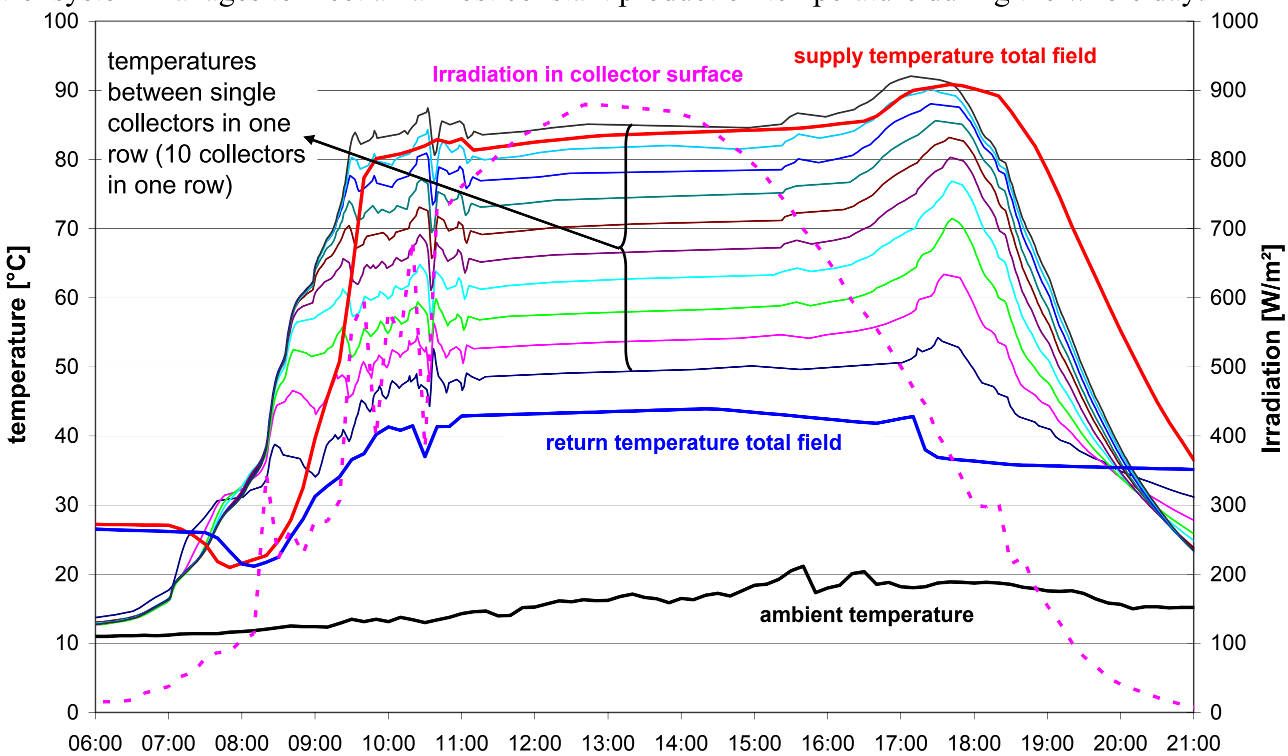


Fig. 2.23: Temperature development within the new Arcon field (09.05.2004)

Figures 2.23 to 2.27 show monitoring values of the efficiency of the collector fields from May to September 2004. The lines give efficiency curves obtained from single collector tests, manufacturer specifications or monitoring results from other sites.

The symbols used in the figures are:

T_{Coll_mean}:	mean Collector temperature $(T_{out}-T_{in})/2$
T_{amb}:	ambient temperature
G_{Coll}:	global irradiation on collector surface
$\Omega = (T_{Coll\_mean}-T_{amb})/G_{Coll}$	reduced temperature

The efficiency values from the monitoring data have been chosen from steady-state periods. This has been done by an automatic filter function that separates nearly constant operational conditions from changing conditions. The criteria for the operational conditions is the reduced temperature Ω. Conditions are assumed to be steady-state if Ω changes not more than $1\cdot10^{-4}$ within 30 minutes. In general it has to be taken into account when comparing efficiency curves from collector test results with monitoring data, that test efficiency curves are usually drawn for a constant global irradiation of 800 W/m², while for monitoring data the irradiation is varying. This results in "efficiency clouds" instead of efficiency lines in the case of monitoring values. Superposed are capacitive effects that still affect the efficiency calculations. They also explain stronger deviations for single points in the following figures.

Figure 2.23 shows the efficiency values for the two Arcon fields. The efficiency values from the measurements from the new Arcon field are slightly below the efficiency curve from the collector test. This is because the test was done for one single collector; the measurement in Marstal is done for the whole collector field including the thermal losses of the piping within the field and to the heat exchanger. The most frequent operation conditions are between Ω = 0.04 and Ω = 0.08.

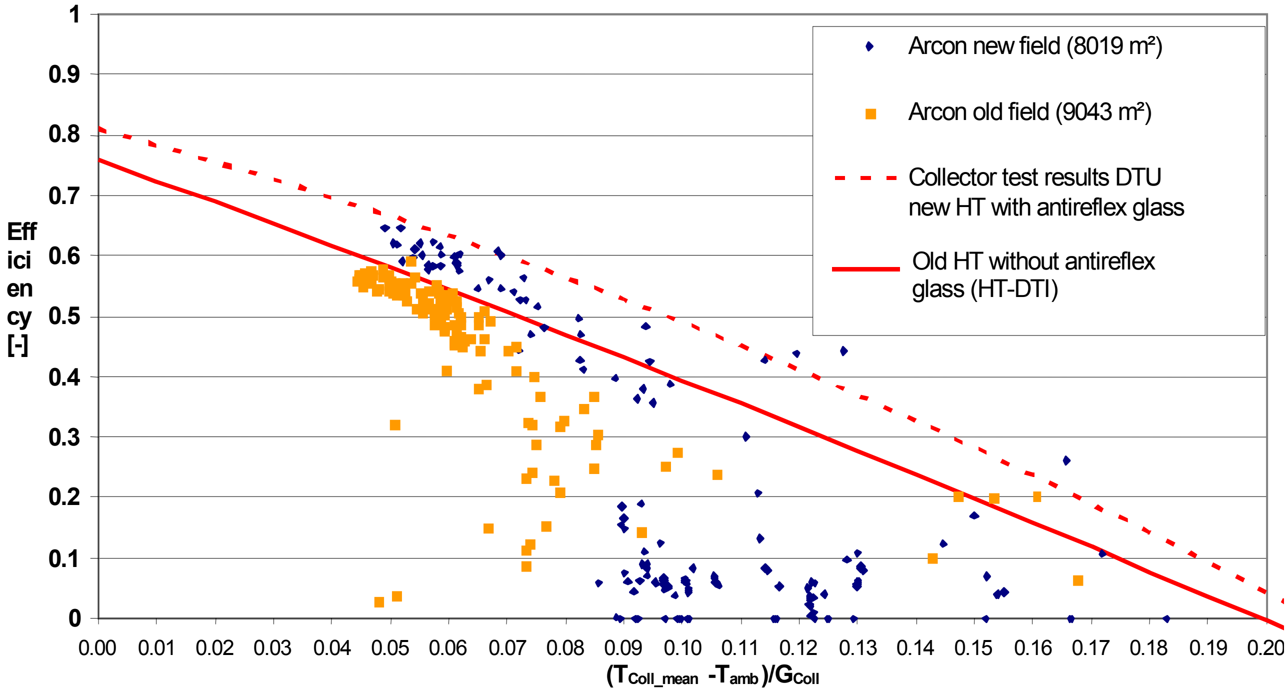
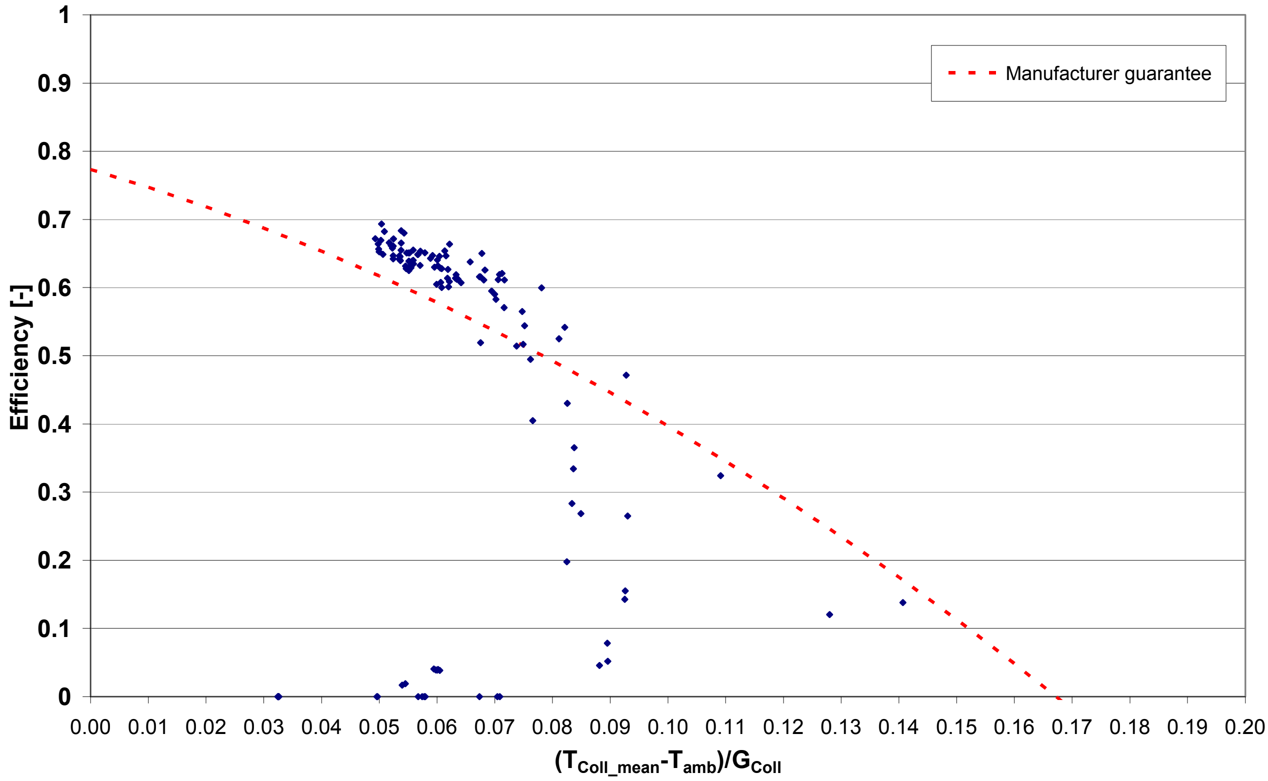


Fig. 2.23: Collector field efficiency Arcon collector fields



Fig, 2.24: Collector field efficiency GJ field (881 m²)

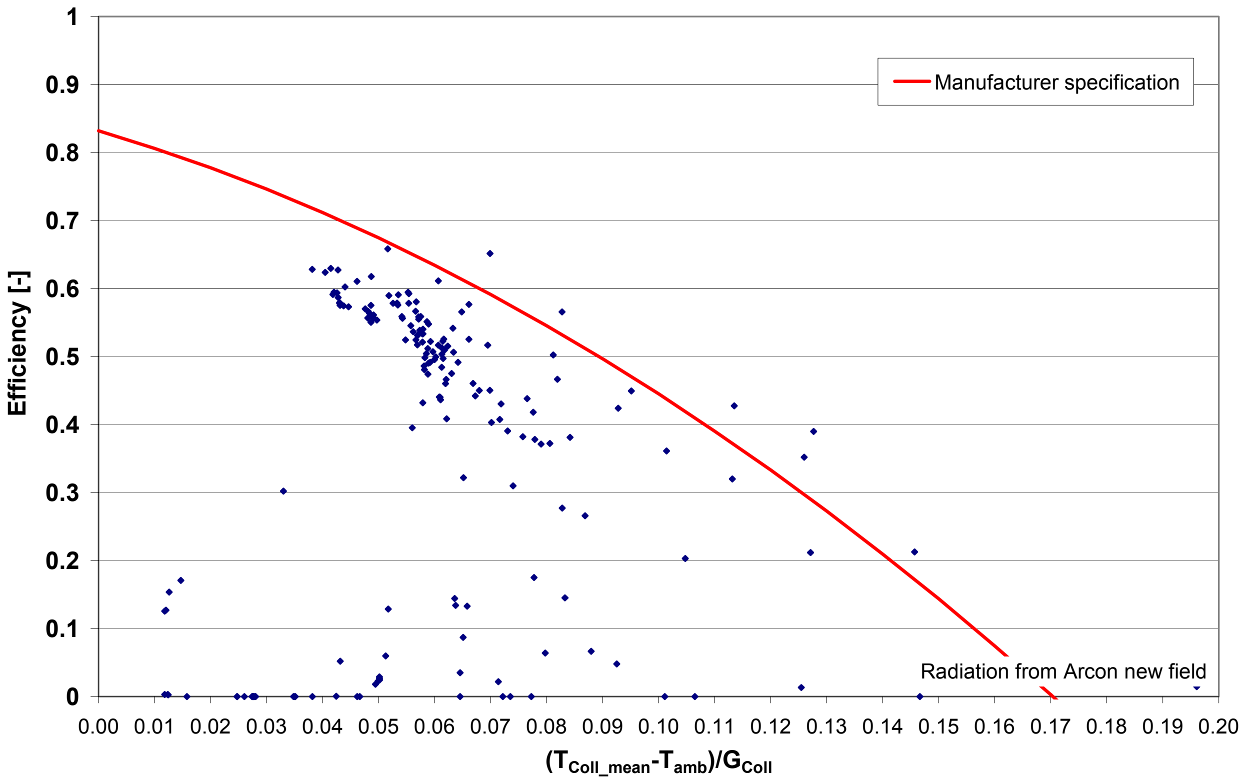


Fig. 2.25: Collector field efficiency Wagner field (103 m²)

The efficiency of the GJ collector field can be seen in figure 9. There are no collector test results available for this collector. The red line gives the efficiency curve that was guaranteed by the manufacturer.
Figure 2.25 shows the efficiency of the Wagner Solar Roof collector. The solar irradiation in this orientation is not measured separately. For this reason the irradiation measurement of the new Arcon field has been used. The slope of the Arcon field is a little higher than the one of the Wagner field. By this the calculated efficiency values, especially outside the summer months, are a little lower than the real values because the used global irradiation is somewhat higher than the real irradiation.
In figure 2.26 the efficiency of the Thermosol vacuum tube collectors can be seen. The operation of these collectors in general took place at lower production temperatures compared to the other collectors as can be concluded already from the reduced temperature Ω. The flow-weighted mean supply temperature was around 55 °C while it was around 80 °C in the new Arcon field.

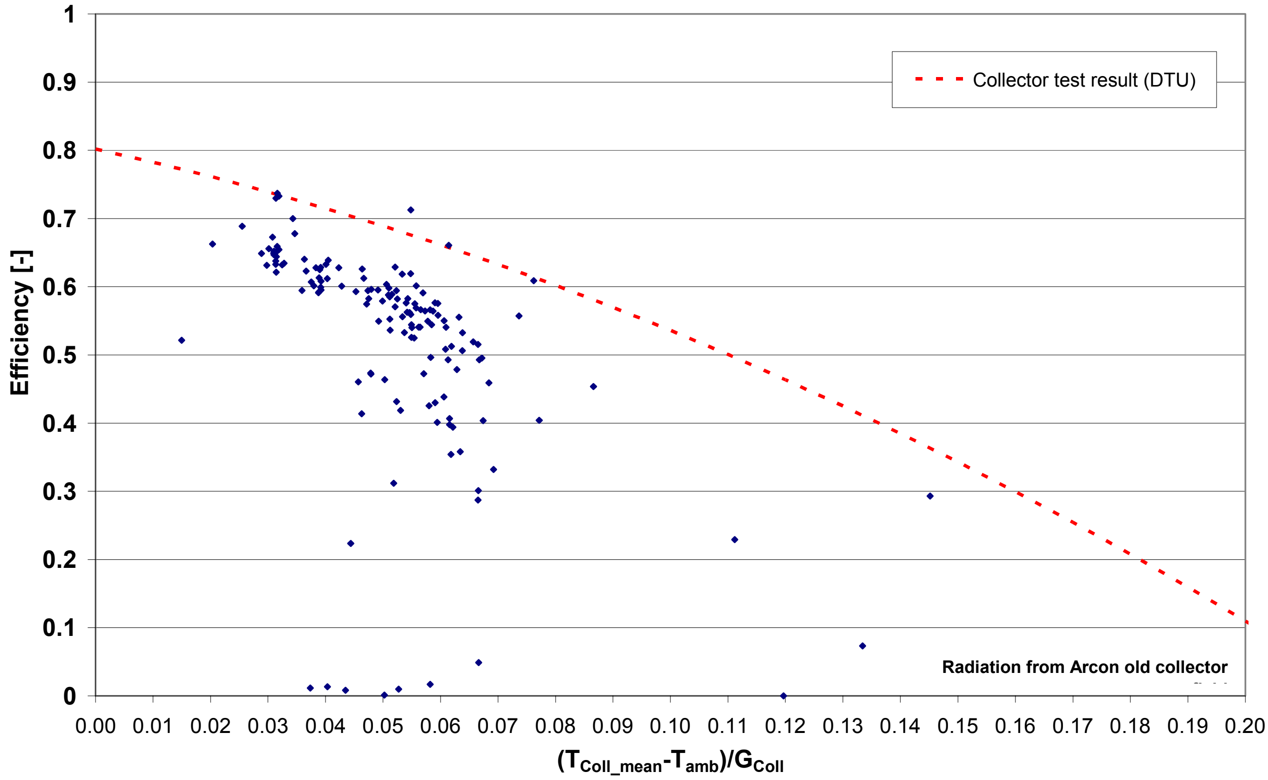


Fig. 2.26: Collector field efficiency Thermosol field (vacuum tube collectors, 108 m²)

The efficiency of the IST parabolic trough collectors is illustrated in figure 2.27. This kind of collector is designed for high temperature applications. This can also be seen from the efficiency curve from the DLR-monitoring: the curve is declining much less than the ones of the flat plate collectors. To take advantage of this behaviour, the IST field in Marstal was also operated at high temperatures. This was realised by using the supply temperature (production temperature) of the new Arcon field as input to the IST field. By this, the temperature of the flow coming from the Arcon field was further increased by the IST collectors. The monitoring values for the flow-weighted mean temperatures are 80-82 °C for the return temperature and between 86 and 89 °C for the supply temperature. Even at these high temperatures efficiencies between 40 and 60 % were reached, as can be seen in figure 2.27. However, despite the good efficiency at high temperatures the total energy production was considerably less than that of the flat plate collectors, as already discussed above.

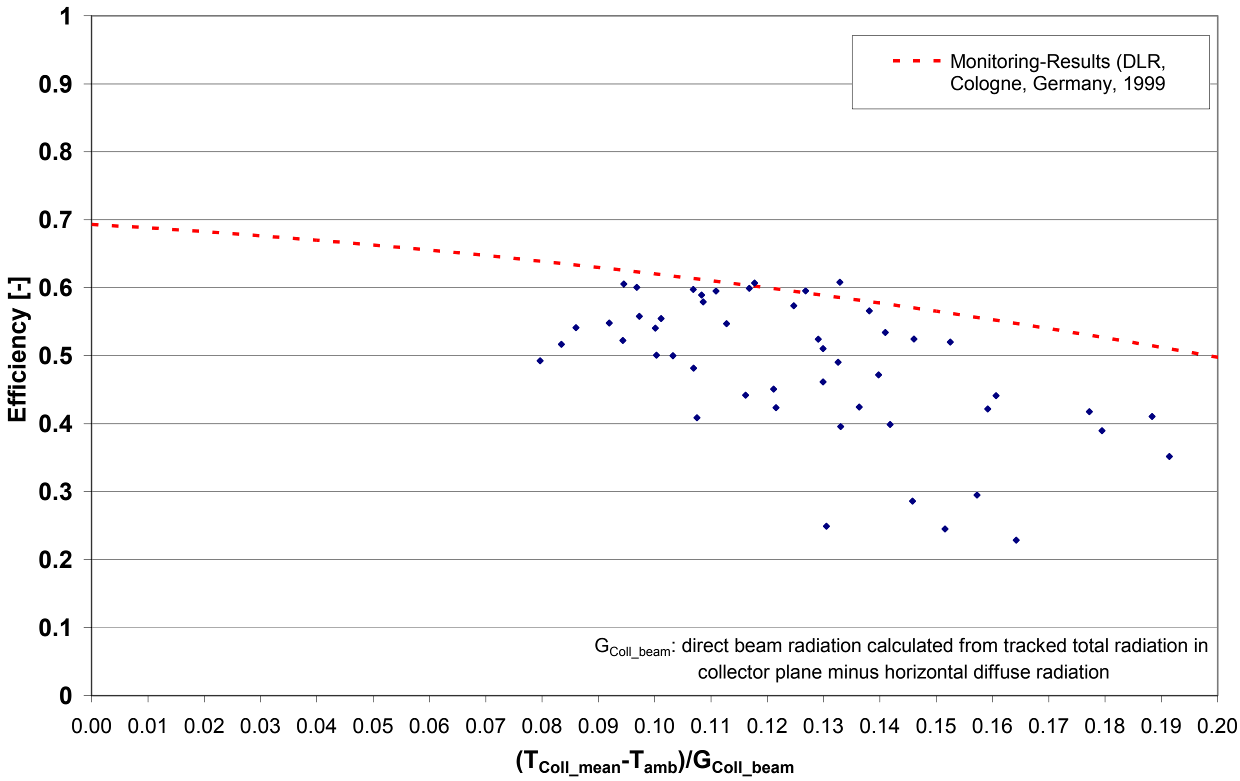


Fig. 2.27: Collector field efficiency IST field (parabolic troughs, 211 m²)

10 000 m³ Pit Heat Store

The pit heat store went into operation in June 2004. Figures 2.28 to 2.30 show the heat balance of the store and the temperature development inside the store in 2004. The main charging took place end of July and beginning of August, where about 430 MWh of heat were charged into the store. After a short discharging period end of August another 163 MWh were charged in September. Altogether 773 MWh were charged into the store in 2004, 273 MWh were discharged until end of November. The change in the internal energy content was estimated to 186 MWh between end of May and end of November. With these numbers an efficiency of 59 % can be calculated for the store. However, it has to be taken into account that the heat losses to the surroundings are higher in the first years of operation than in the long run, see below.
The maximum temperatures reached 77 °C in September (figure 2.30) at the top of the store; the maximum mean temperature was 60 °C. The highest stratification between top and bottom of the storage volume was 40 °C at the end of the charging period beginning of August.

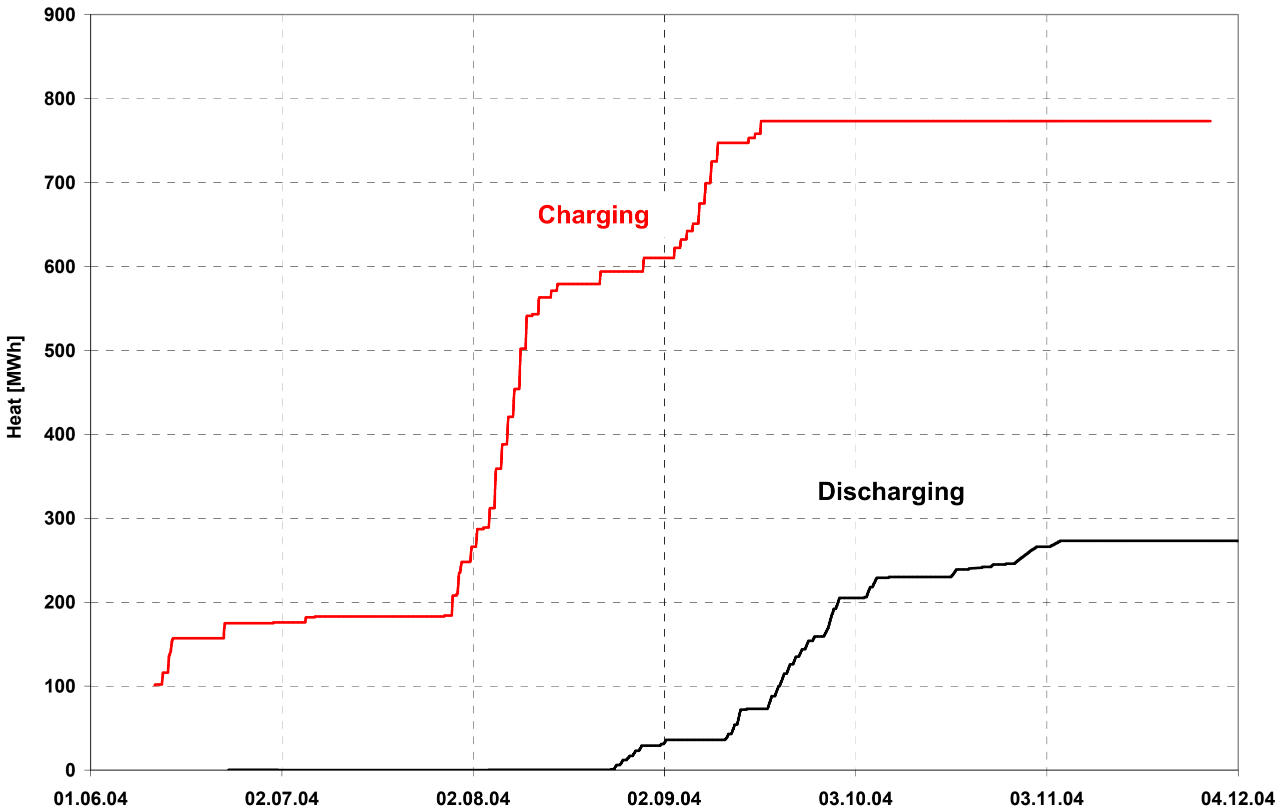


Fig. 2.28: Charging and discharging of the pit heat store

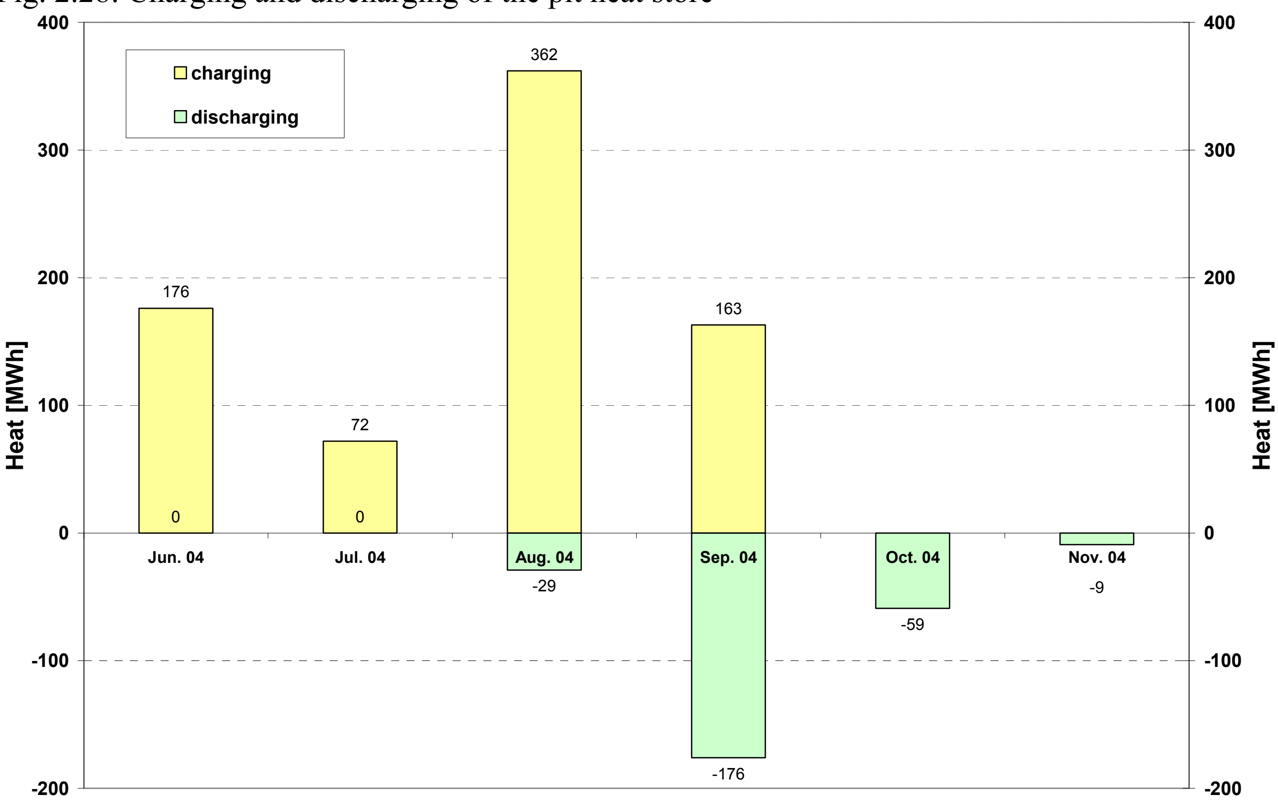


Fig. 2.29: Heat balance of the pit heat store from March to November 2004

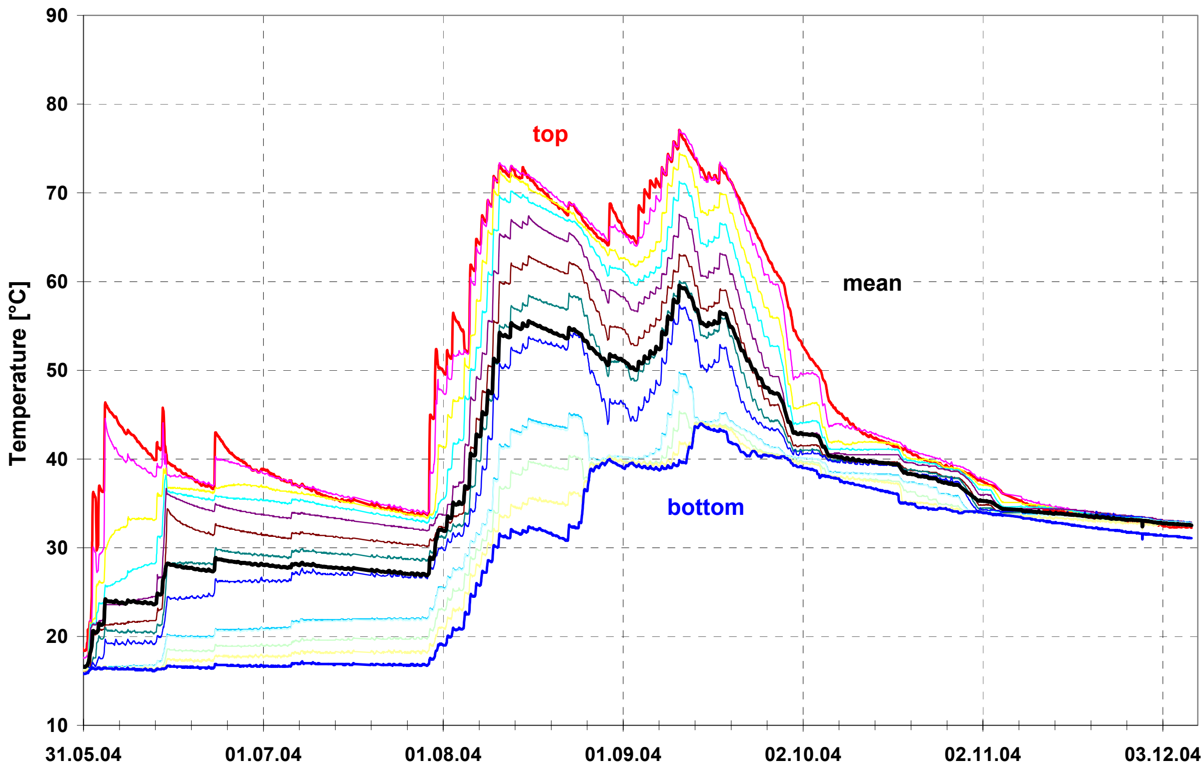


Fig. 2.30: Charging and discharging of the pit heat store

The ground around the pit heat store is heated up due to the transmission heat losses through the side walls and the bottom. The yearly mean temperature of the surrounding ground will increase in the first years because of these heat losses. After a start-up period of three to five years, where the yearly heat losses will continuously decrease, the yearly mean ground temperatures will not change anymore and the store is operating under steady-state conditions.
Because of the start-up period, the temperature changes in the store and the temperature changes at the ground surface the temperature development around the store will have a seasonal and a long-term component. The seasonal component will follow the temperature development at the surface and inside the store with a delay.
Figures 2.31 and 2.32 show the temperature development in the underground around the store (for sensor positions see also figure 2.17). The lines in the charts show the temperatures at a certain date, the single charts give the temperature developments at certain locations around (A – D, F, G) and inside (E) the store. The time period comprises the charging and discharging processes in 2004. Figure 2.31 shows a vertical section in south-north extension, figure 2.32 in west-east extension. The seasonal component can be observed in the charts down to the depth of the storage bottom. In the first meters below the ground surface the temperature development follows the ambient temperature. Below the bottom of the store only an increase of the temperature can be determined.

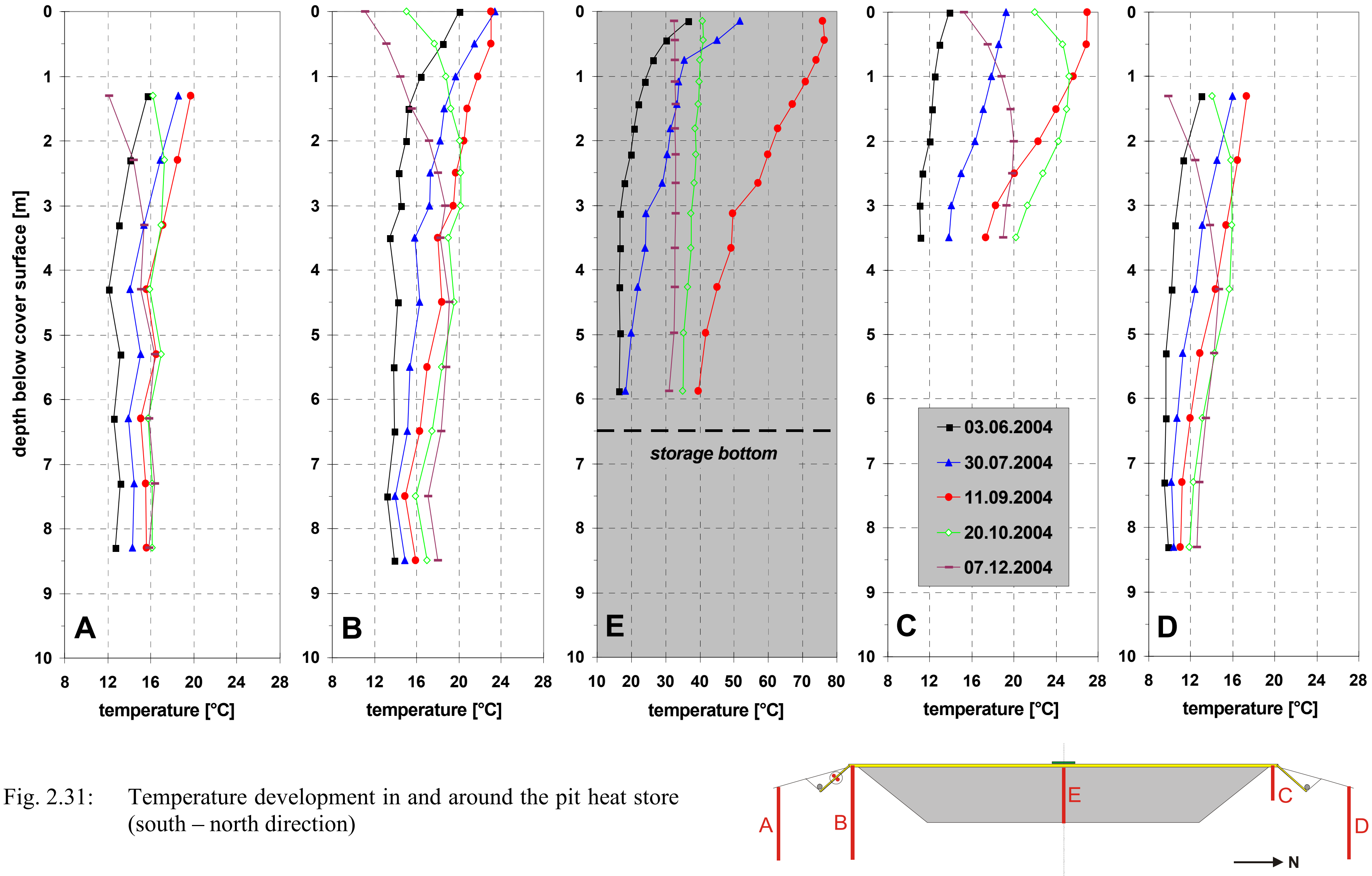
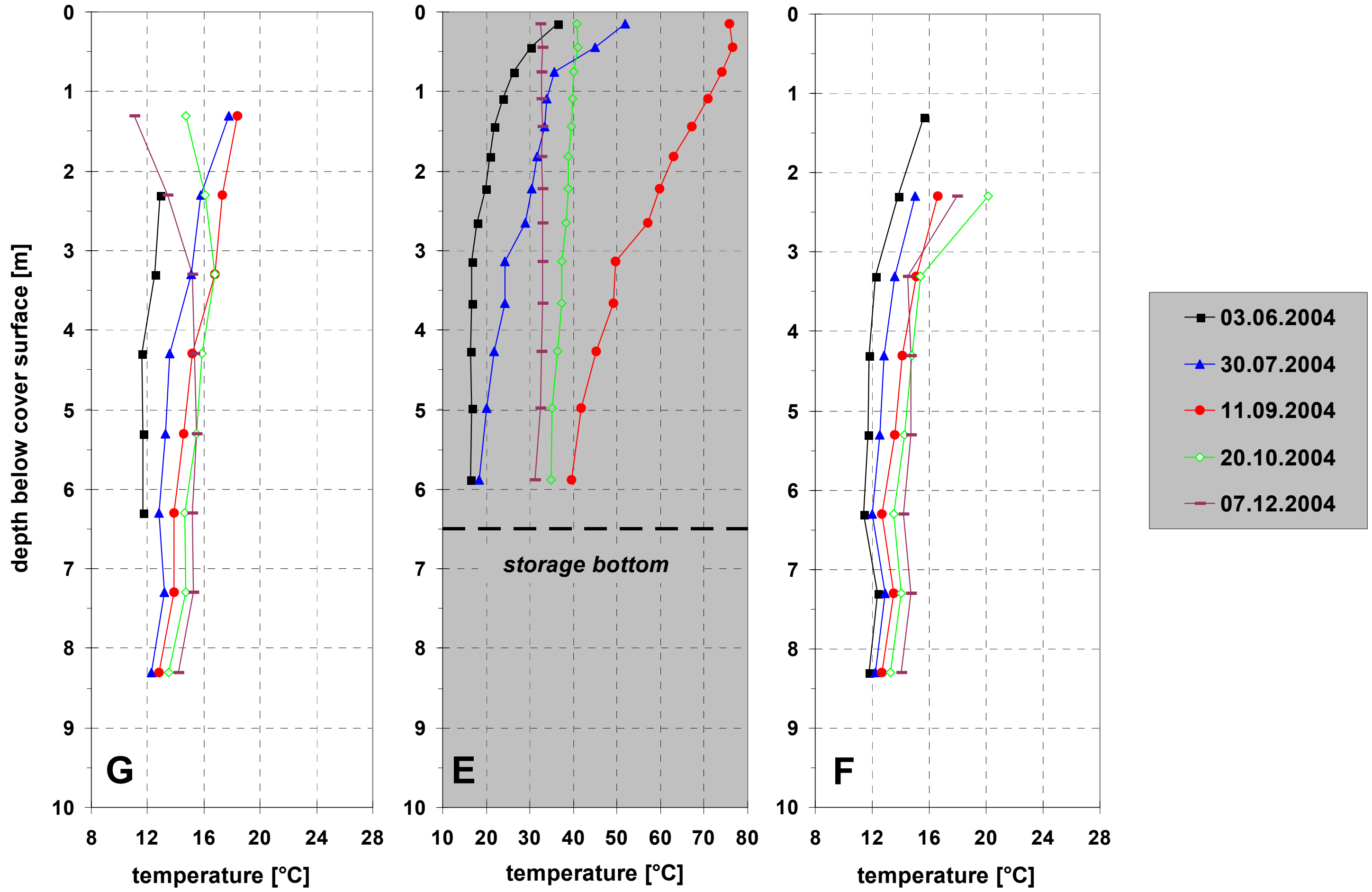


Fig. 2.31: Temperature development in and around the pit heat store (south – north direction)



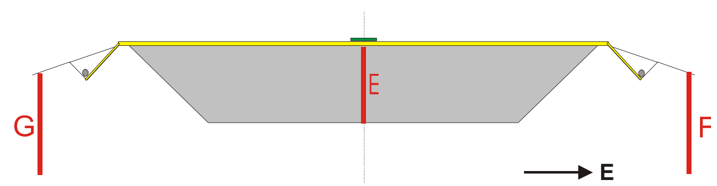


Fig. 2.32: Temperature development in and around the pit heat store (west – east direction)

The dispersion of the ground temperature field is not equal as can be seen when comparing north with south and east with west temperatures. In chart A temperatures are in general 2-4 K higher than in chart D, in chart G slightly higher than in chart F. This could be an indication for a low natural groundwater flow in south / south-west direction. On the other hand, chart C gives higher temperatures than chart B, which seems not to be reasonable. An explanation could be a higher thermal conductivity of the ground in the area of the temperatures of chart C caused by a leakage that was detected and fixed after the construction period of the store. Because the ground in this region is more wet than on the south side it has also a higher thermal conductivity and causes higher heat losses.

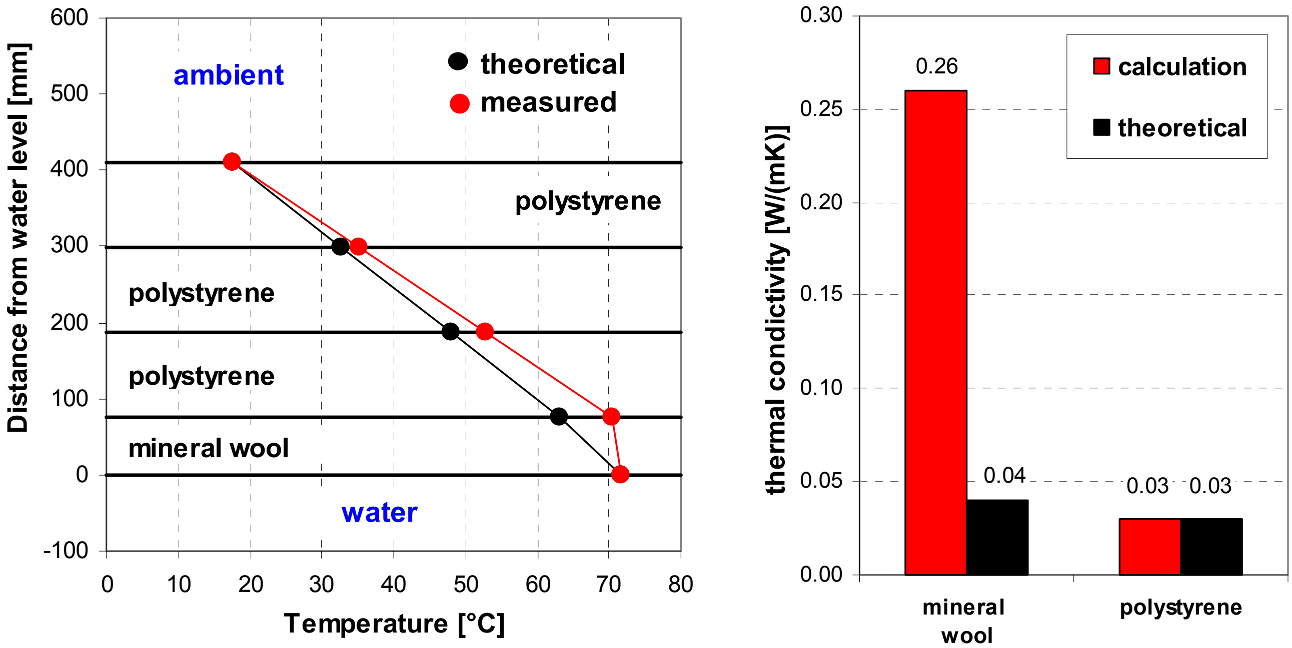


Fig. 2.33: Temperature gradient inside the cover construction (left) and theoretical and calculated thermal conductivities of the insulation materials (August 14th 2004)

In the floating cover temperature sensors have been installed between the different insulation layers. An evaluation of these temperatures is shown for August 14th in figure 2.33 on the left side. The temperature decrease in the mineral wool is much less than expected. These conditions can only be explained by moisture that entered the insulation material. A visual inspection by Marstal Fjernvarme in November 2004 confirmed moisture in the construction. The actual thermal conductivities of the insulation materials can not be calculated exactly from the monitoring data because the heat flux sensor that was installed in the same place as the temperature sensors is not working. Nevertheless the thermal conductivity of the mineral wool can be estimated by the ratio of the thermal conductivity of mineral wool to that of polystyrene which can be calculated from the temperature differences. This ratio varies between 8 and 10 in August and September 2004; the theoretical value is 0.04/0.03 = 1.33. On the day shown in figure 2.33 the ratio was 8.7. Under the assumption that the polystyrene still has its theoretical value (polystyrene is much less vulnerable to humidity than mineral wool) the thermal conductivity of the mineral wool can be calculated to 0.26, see figure 2.33 right side. If this situation applies for the whole cover area the yearly heat losses through the cover are approximately 15% higher than designed (for 30 K mean temperature difference between store and ambient). Furthermore, if it is not possible to find the reason for the moisture content and to dry the construction, care has to be taken on the allowable maximum temperatures of the polystyrene.

The service temperature for common polystyrene material should not exceed 80-90°C for a short time and 70-80 °C in the long run.

Summary

The Marstal Solar Heating Plant has been equipped with an extensive monitoring system. After the extension of the plant it continued recording data in September 2003. The monitoring system allows a detailed investigation of the efficiency of the different components, the operational conditions and the long-term behaviour of the whole plant and its components. Due to initial problems with the database no data is available for January to mid of March 2004.
The evaluation of the solar collector fields shows a high productivity of the vacuum tube and the flat plate collectors. Specific heat productions from March to September 2004 range from 358 to 389 kWh/m² for the new flat plate collectors and 429 kWh/m²a for the vacuum tube collectors. Because of their size the two Arcon fields deliver the major solar contribution to the heat supply. During the summer months the solar collectors were able to cover almost the total heat demand of the plant. Additionally surplus heat could be stored into the seasonal heat store.
The parabolic trough collectors delivered less than half of the specific heat production (142 kWh/m²) of the flat plate collectors. An explanation for this is the high fraction of diffuse irradiation which cannot be used by this type of collector. Nevertheless the adjustment of the focusing system and the operational parameters should be checked continuously.
The new 10 000 m³ pit heat store went into operation in May 2004. By now one cycle of charging and discharging has passed. The efficiency of the store can be calculated to 59 % in the period May to November 2004 including the change in the internal energy content. This number will increase in the following years due to decreasing heat losses to the surrounding ground.
By now maximum temperatures reached 77 °C on top of the store. Care has to be taken on the maximum temperatures for the polystyrene material in the floating cover: as a result of a higher thermal conductivity of the mineral wool insulation layer due to moisture content the temperatures for the polystyrene are significantly higher than expected. As a result, yearly heat losses through the cover can be up to 15% higher because of this.

2.2.8. TRNSYS Calculations

Comparison between Calculations and Measurements.
In the detailed design of the new solar collector field was developed a Trnsys model, which included the whole Marstal District heating plant, that is with both the new and the original collector field, the steel tank and the new pit storage. The Trnsys model simulated the system over a period of four years. The long simulation period was chosen in order to have the pit storage in balance with the surrounding earth.

The storage in the TRNSYS model is a truncated cone, while the actual storage has shape as a wedge. The volumes are the same but the surface of the TRNSYS storage is consequently a little smaller resulting in a smaller heat loss.

Data collection
The data monitoring did in the initial stage have some problems resulting in periods with errors or lack of data. In this comparison is looked upon data from September 2003 to September 2004.

From the monitoring system hourly values of ambient temperature and solar radiation has be extracted.

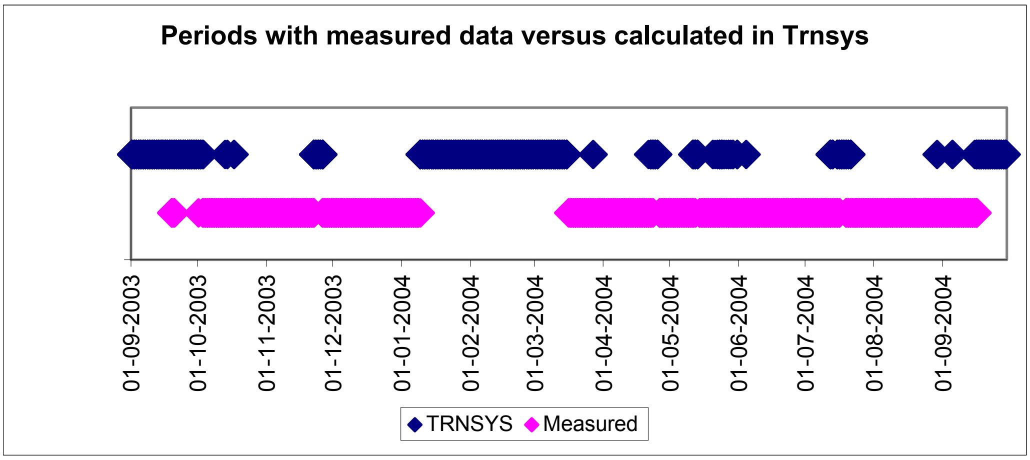


Fig. 2.34 Measured data versus calculated in TRNSYS

As it shows, there was a longer period from start of January to mid March where the data logging has failed. Beside that there have been shorter periods with errors.

Revised TRNSYS model.

The TRNSYS model has subsequently been altered. In the new model the measured data now replaces the original TRNSYS data according to the periods shown in 2.35.

Comparison, Monthly values

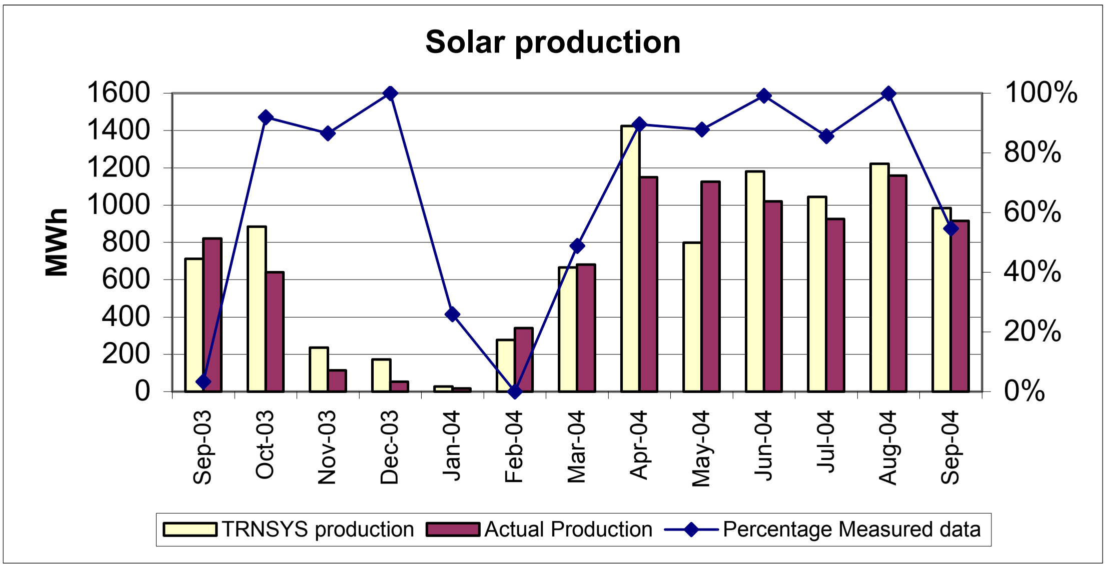


Fig. 2.35 Solar production

In Fig. 2.35 is shown the monthly solar production calculated by TRNSYS when using measured weather conditions and the actually measured solar production.

The TRNSYS production is lower than the actual production in May, but higher in April and in June to August.

Taking a closer look at a single month, August 2004, the daily production appears as in Fig. 2.36

It appears that the production calculated in TRNSYS, based on the measured solar radiation is little higher than the actual production, in average around 5%. One reason for this higher production can be the fact that the measured radiation is without array shading. In the original TRNSYS model is included array shading, but due to the nature of the measured radiation data, it is not possible to include it in the present model.

The impact of array shading, i.e. the rows of collectors are in shadow of the row in front, has been analysed earlier in this project. From those calculations can be extracted that the impact of array shading is approx. 4% in August.

Thereby it can be concluded that the TRNSYS model generates a solar production close to the actual production.

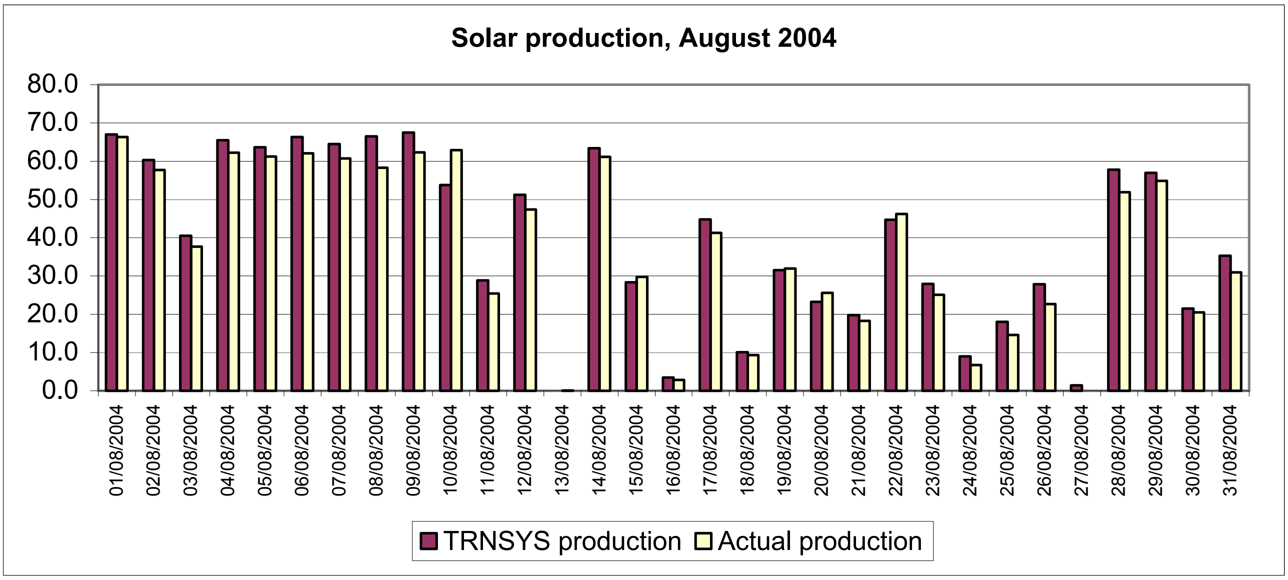


Fig. 2.36 Solar Production, August 2004.

Energy in and out of Pit Storage
In relation to the pit storage the following data have been calculated and measured:

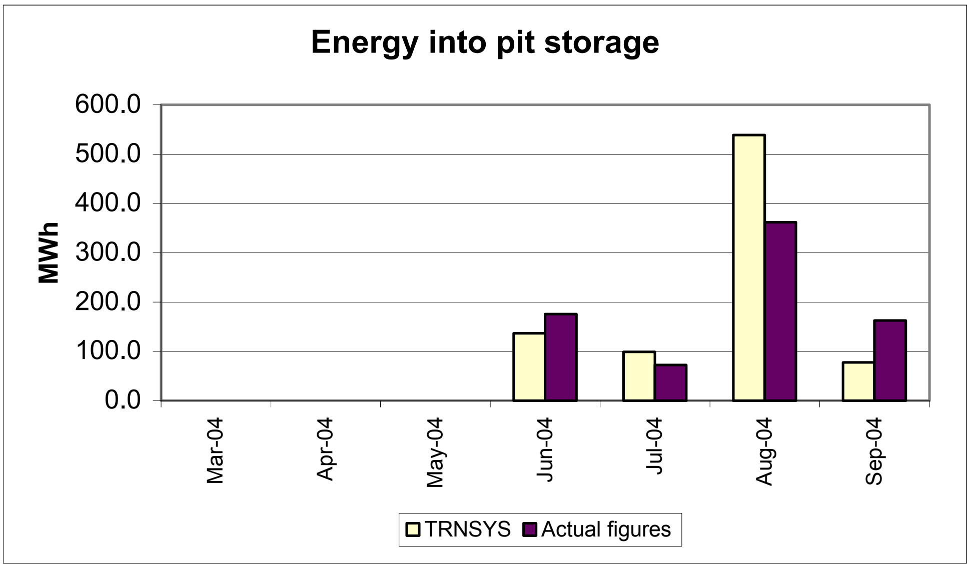


Fig. 2.37 Energy into pit storage

Comparing the TRNSYS production with the actual energy input there is some fluctuation. Summing up the figures from June to September TRNSYS calculates an energy input of 851 MWh, where the actual input was 773 MWh.

When it comes to energy out of the storage the following figure appears. The period has been extended to the end of the year. Here the fluctuation is even more distinct.

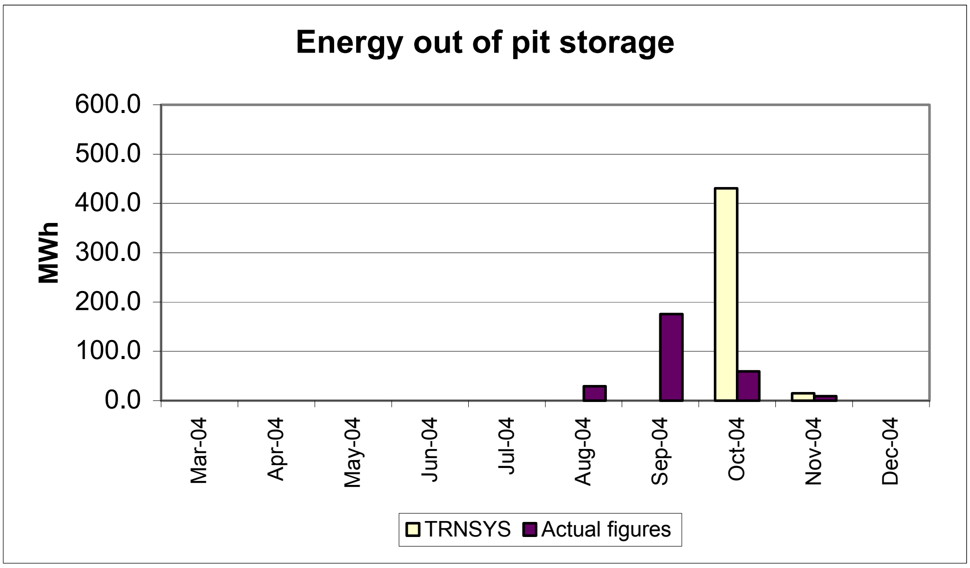


Fig. 2.38 Energy out of pit storage

Adding the figures from August to December the model has an energy outtake of 446 MWh, where the actual outtake was 273 MWh. The energy loss in the storage, calculated as difference between input and output, was in TRNSYS 406 MWh and in the actual storage 500 MWh.

Temperatures in Pit Storage

Below in figure 2.39 is illustrated the temperatures in the storage as calculated in TRNSYS, looking at the period from the end of May to end of the year.

In figure 2.40 is illustrated the actual measured temperatures in the same period. Finally in**Fejl! Ukendt argument for parameter.**2.41 is combined the top layer and the bottom layer temperatures from the two graphs.

The top temperature in TRNSYS is around 88°C where the actually top temperature only reaches approx. 75°C.

The temperatures in the two storage follows until August, where the temperatures in TRNSYS are increasing more, due to the higher energy input.

The actual top temperature decreases faster than in the model. The reason is that the major part of the actual energy outtake happens in September, where TRNSYS has at big outtake in October. From November both top and bottom temperatures in both cases is around 35-40°C.

Comparing the starting temperatures and the end temperatures in figure 2.41 is shows that the loss calculated above is overestimated. Setting the temperature difference to 12°C the energy content in the storage is 140 MWh higher at the end of the year, reducing the loss in the TRNSYS model to 266 MWh and in the actual storage to 360 MWh. Further should be noticed that energy dispersing into the surrounding ground heats up the ground and subsequently reduces the losses the following years.

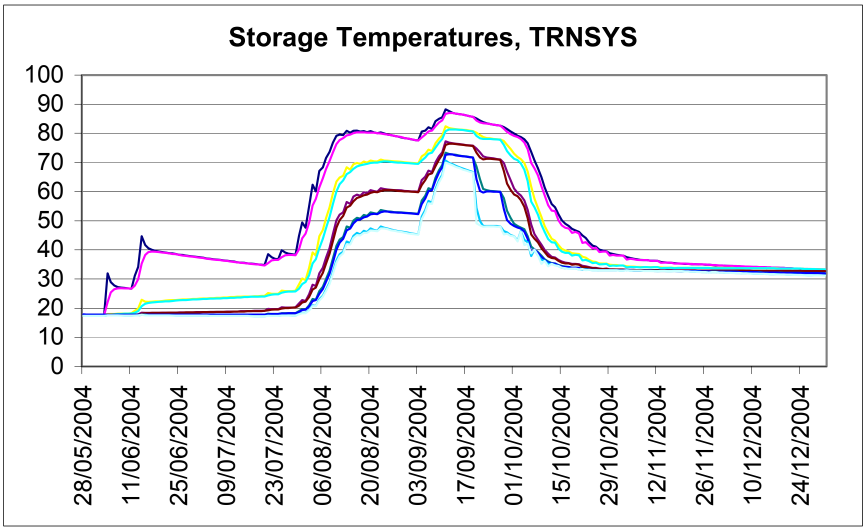


Fig. 2.39 Storage Temperatures, TRNSYS

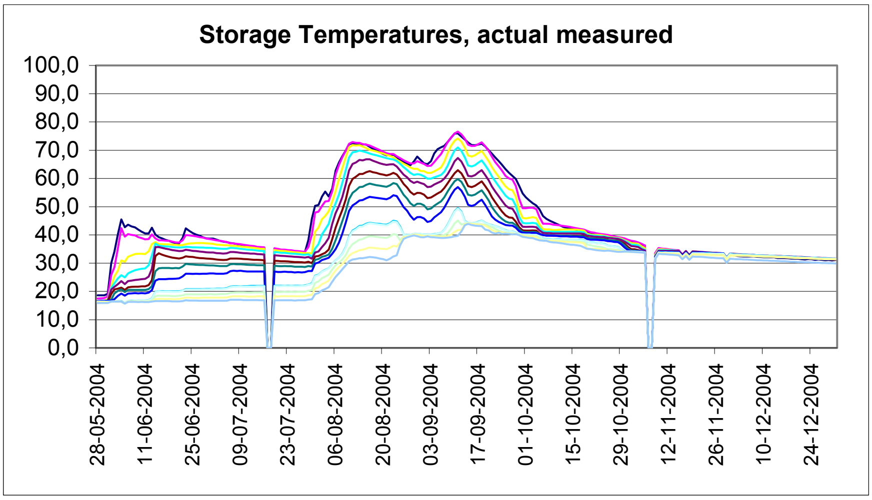


Fig. 2.40 Storage Temperatures, Actual measured.

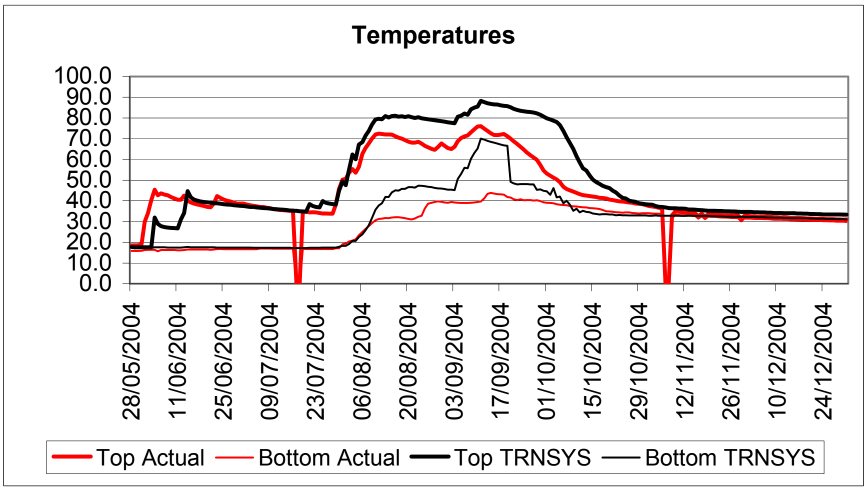


Fig. 2.41 Storage temperatures, combined

Conclusion
The TRNSYS model calculates the solar production very close to the actual production, but the loss from the actual storage is 1/3 higher than the loss from the TRNSYS model.

2.2.9. Dissemination
Dissemination has taken place as follows:

www.solarmarstal.dk
The Marstal District Heating homepage presents the complete energy system and production results are transmitted continuously. Monitoring files can be downloaded.

Guided visits
In the period July 2001 - December 2004 12172 guests have been shown around in the solar plant, among them visitors from 22 district heating companies in Denmark and 3 district heating companies from other European countries. Among the visitors have been foreigners, representing 27 countries. (Holland, Romania, Turkey, Sweden, Germany, Canada, Australia, China, United States, Great Britain, Vietnam, France, Poland, Korea, Norway, Spain, Schwitzerland, Austria, Latvia, Russia, Estonia, Italy, Japan, Thailand and India) and 364 representatives from universities and other technical educational institutions.

Local workshop for European participants
In September 2004 Marstal District heating had a workshop in which the project was introduced along with a programme containing status and possibilities for development concerning large solar collector fields and long term heat storages. 36 persons from 7 countries participated and the programme was as follows:

15.00	Arrival and registration at Hotel Ærø Strand
16.00	Welcoming and guided tours on Marstal District Heating Solar plant A plant with 6 various kinds of solar collectors, all in all 18.300 m^2 and 3 various kinds of storages, all in all 14.000 m^3 water storages. Presentation by: Niels Aage Jensen and Leo Holm from Marstal District Heating
18.00	Dinner
19.30	Pictures and video from the building period of the latest 9 300 m^2 of solar collectors and the 10 000 m^3 pit heat storage. Experiences from the building period. Presentation by: Flemming Ulbjerg from Ramboll and Leo Holm from Marstal District Heating
27.09.04	
09.00	Optimizing of a 12.5 m^2 flat plate collector. Presentation by: Leif Tambjerg from PlanEnergi Measuring results from the 6 various solar collector fields in the Marstal plant. Presentation by: Thomas Schmidt and Dirk Mangold from SWT, Stuttgart
10.00	Presentation of new solar plants and projects for heat- and cooling plants, with large scale solar fields in Europe. Projects in Austria by the firm S.O.L.I..D Projects in Sweden by Jan-Olof Dalenbäck, CIT, Göteborg Projects in Polen by Michal Ciechorski Projects in Denmark by Per Alex Sørensen, Projects in... (Holland, France, Spain ?)
12.00	Lunch
13.00	Design and building of the 10.000 m^3 pit heat storage in Marstal Presentation by: Flemming Ulbjerg from Ramboll and Ebbe Münster from PlanEnergi
14.00	Status for storage development in Europe and possibilities for support from the European Union. Presentation by:Fabian Ochs from ITW, Stuttgart Thorsten Urbaneck from Technische Universität Chemnitz Mrs Ingrid Weiss form the European Union Presentation of new development and demonstration projects.
16.00	Study tour to Rise and Ærøskøbing District Heating

18.00 Dinner
28.09.04
09.00 Presentation of solar collectors from ARCON and GJ Teknik
The market for large scale solar heating and cooling plants in Europe.
Discussions- co-operation - new projects – questions of general interest

The presentations may be found at www.solarmarstal.dk.

Presentations
The project has been presented at the following events:

- 2001.
  Presentation at Exhibition Center Herning, DK
  Poster at a conference in Bryssels, B
  Presentaion i Göteborg, S
  Presentation at AJOUR 2001, DK

- 2002.
  Presentation at rural district conference, DK
  EUROSUN 2002, Bologna, I. Paper:
  ”SUNSTORE 2. 10 000 m^2 of Solar collectors and 10 000 m^3 water storage in Marstal. DK.

  Presentation in Korea.

- 2003
  ISES 2003, Göteborg, S. Paper:
  SUNSTORE 2. Design and construction of the largest solar thermal system in the world. Status Spring 2003.

  Presentation for delegation from Korea.

  Presentation for GJ-Tekniks partners from GB.

- 2004

  Presentation for delegation from Romania

  EUROSUN 2004, Freiburg, DE. Paper:
  Monitoring results from the project and construction of 10 000 m^3 pit heat storage
  presentation in Salzburg, A.

  Presentation in Vietnam.

  Presentation in solar conference in Copenhagen, DK

Presentations in public media

TV Fyn (local) 3 times during the building period.
DR1 (Danish national)
DR2 (Danish national)
Norwegian, German, Korean and Italian TV

Radio
Radio Fyn (local), NDR (Germany) and Norwegian Radio

Newspapers
Jyllandsposten (Danish), Politiken (Danish), Fyns Amtsavis (Danish), Fyns Stiftstidende (Danish), Kieler Nachrichten (German) have all brought articles about the project.

Finally the project has been presented in several Danish technical periodicals: Fjernvarmen, Ingeniøren, Vedvarende Energi og Miljø, VVS-bladet a.o.

A video of the construction of the plant is available.

2.3. Assessment of Results and Conclusion

The scientific and technical objectives are reached as follows.

The design of a pit heat storage to be constructed at less than 67 €/m^3 at a size exceeding 10 000 m^3 and less than 30 €/m^3, at a size exceeding 50 000 m^3.

The 10 000 m^3 pit heat storage in Marstal is constructed at 67 €/m^3 (price level 2004). That is slightly cheaper than the objective of 67 €/m^3 (price level 2001). It has to be mentioned that the price does not cover a technical building of same size and quality as in Marstal.

Using the same price/unit as for the 10 000 m^3 storage, the costs of a 100 000 m^3 storage can be calculated

	Costs (1.000 €)	**Costs €/m^3)**
Excavating	761	7,6
Side- and Bottom liners	184	1,8
Cover	1 516	15,2
Draining	26	0,3
Intake and outlet	268	2,7
Control system	67	0,8
Other costs 10%	282	2,8
Total	**3 104**	**31**

The price level is 2004. This has to be compared with the 30 €/m^3 (price level 2001) promised in the application.

The design of a ground mounted flat-plate collector with an efficiency improvement of at least 10% without a corresponding increase of the price.

The efficiency improvement is measured by Danish Technical University and calculated in TRNSYS to be 19% and the price is 5% higher for the new developed HT-collector. Thus the cost-efficiency is calculated to be 13% higher. The measured improvement for the new HT-collectors in the collector field in Marstal is less than 19% compared to the old collector field. But the new HT-collector is producing approximately as expected when we compare with the efficiency curve measured by Danish Technical University and with calculations in TRNSYS.

Demonstrate a 10 000 m^3 pit heat storage with a floating cover. Demonstrate a 10 000 m^2 solar collector field, divided in parts adapted for different levels of temperatures. Hereby both different types of ground-mounted flat-plate collectors will be demonstrated as well as focusing solar collectors. Thus district heating companies, for example, will be able to receive information about performance and experiences concerning maintenance under identical conditions for different types of solar collector fields. Heat storage and solar collector field will be demonstrated in the town of Marstal, Denmark.

The 10 000 m^3 pit heat storage with floating cover is established and a solar collector field with

8 109 m^2	new ARCON-HT collectores (flat plate ground mounted)
881 m^2	GJ-Teknik collectors (flat plate ground mounted)
211 m^2	IST-collectors (focusing, ground mounted)
108 m^2	Termomax collectors (evacuated tubes, ground mounted)
103 m^2	Wagner collectors (flat plate roof modules)

is established.

Integration of solar heating in a conventional district heating system. Solar fraction 30%. Price of energy 0.045 €/kWh.

In Marstal 8 019 m^2 of new ARCON-HT collectors and 10 000 m^3 pit heat storage has been established for less than 2,28 mio € (17 mio. DKK). The production is around 3 800 MWh/year. If the financial costs are 6,7 %/year, the heat price is 0,04 €/kWh. This is calculated for the last 8 000 m^2 in a 19 000 m^2 plant covering 30% of the annual production in Marstal. A calculation for a new plant of totally 19 000 m^2 covering 30% will show an even lower heat production price/kWh.

Conclusion

The objectives in the project have according to the above mentioned results been met.

2.4. References

1. Fastlæggelse af levetider for 2 HDPE plastlinere til sæsonvarmelagre. Søren Pedersen, Teknologisk Institut 2004 (in Danish).
2. Udvikling af flydende lågkonstruktioner til damvarmelagre. Institut for Bygninger og Energi, DTU 2000. Sagsrapport SR-0009 (in Danish)
3. Marstal 10 000 m^3 seasonal storage. Insulation of sides. Vapour and condensation. Insulation of lid. Ebbe Münster, PlanEnergi, 2003.

3 Management Final Report

3.1. List of Deliverables

Deliverable No	Deliverable title	Delivery date Promised	Actual	Dissemination level
1	Design report	6	13	RE
2	Tender documents	9	13	RE
3	Contracts	11	13	RE
4	Approvals	12	13	PU
5	Long term storage	24	29	PU
6	Solar collector plant	27	24	PU
7	Final report including results of measurements	36	44	PU/RE

RE = Restricted, PU = Public

3.2. Comparison of initially activities and work actually accomplished

During the project there have been a few deviations from the initially work program

- Evacuated tube collectors have been included in the test field.
- Implementation of the 10 000 m^3 pit heat storage was postponed nearly one year because we had to wait for results from test of HDPE-liners. That ment that parts of the solar collector field had to be covered with greenhouse painting in the summer of 2003.

Despite of that we followed the work programme.

3.3. Management and Co-ordination aspects

During the project co-operation between the partners has been excellent and design problems have often been solved in common. Thus the technical co-ordination has been without problems.

During the management period we had to make internal changes in the budget. That has taken too long time partly because the rules (annex 2) was not understood correctly and partly because it is very difficult to know exactly how to administrate a project from reading annex 2.