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Case study on district heating based on solar with seasonal pit storage in Marstal, Denmark

Photo: Marstal solar plant with heat storages (source: Marstal Fjevarme A.m.d.b)

For more information

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Introduction

General information[1]	
Solar thermal collector area	33,365 m^2 solar collectors
Thermal energy storage	Pit seasonal storage 75,000 m^3 and pilot heat storage 10,000 m^2
Tank thermal energy storage (steel tank, load balancing)	2,100 m^3

[1] Franz Mauthner and Martin Joly, Analysis of built best practice examples and conceptual feasibility studies of solar thermal systems in urban environments, *IEA SHC,* 9, 31 August 2017.

Other energy sources in district heating system	4 MW biomass boiler with 750 kW Organic Rankine Cycle (ORC) unit
	1.5 MWth electrical heat pump
	Bio oil boilers
Annual solar energy yield	28,000 MWh
Solar fraction	41 per cent (based on heat generated respiration final district heat output)
Specific annual solar energy yield	440 kWh/(m^2gross·a) / 448 kWh/(m^2aperture·a), 2013/2014
Length of the network	19.5 km distribution and 17.7 km service pipes
Number of consumers	1,481

The Marstal solar heating plant is located on Aeroe, a renewable energy island south of Denmark. It is among the largest solar plants in the world and is one of the pioneer pilot projects of its kind. Although Marstal is recognised worldwide for its seasonal pit storage systems, the local community should also be recognised for its commitment to developing district heating based on renewables, showing great openness and acceptance towards new clean technologies.

Since 1994, Marstal District Heating (Marstal Fjernvarme) has been gradually transitioning to a renewable energy system. Today, the company provides heat to the settlement of Marstal from 100 per cent renewable energy sources. Fifty percent of its heat comes directly from the solar heat collectors, 40 per cent from wood chips and two to three per cent from a heat pump.

In 2001, Marstal District Heating received a grant from the Danish Energy Agency and the EU’s Fifth Framework Programme which allowed for solar thermal to cover up 13 per cent of the total heat demand (project SUNSTORE 2), and in 2010 received financing from the EU's Seventh Framework Programme for solar thermal to cover up to half of the heat demand (project SUNSTORE 4). The total budget for the project was EUR 15.1 million, out of which EUR 6.1 million in grants was provided by the EU. The participating partners contributed EUR 0.4 million to the project.

Why pit seasonal storage supported by solar thermal plant was selected

The yearly solar radiation in Denmark is approximately 200 times the amount of energy the country uses yearly for heat, electricity, transport, etc. Marstal decided to take advantage of this and became a demonstration and testing site for national and global clean heating solutions.

The purpose of the SUNSTORE™ concept implemented in Marstal was to show that district heating can be produced with 100 per cent renewable energy sources, of which solar thermal can cover 50 per cent or more. This is done by implementing a large heat storage system in the production system. The concept, based on the pit thermal energy storage (PTES), made it possible:

- to use all types of renewable heat, waste heat and heat pump technology (solar thermal, geothermal, biomass, excess heat from industries);
- to provide consumers with district heat from renewable energy sources without the use of biomass and waste oils;
- to consume and produce electricity when needed in the electricity system and thus to integrate fluctuating electricity production from wind and solar;
- to provide hot water to nearly all of the 2,200 inhabitants of the island town of Marstal;
- to secure a heating concept that can be built up gradually.

It has been estimated that the SUNSTORE 4 project will produce heat at a cost of EUR 50 to 60 / MWh. Compared to heat production prices in 2010, which were more than EUR 70 / MWh and produced from bio-oil, this is a much more cost-effective solution.

Technology and investment costs

The Marstal solar heating plant has been under continuous development throughout the years, mostly due to an increase in consumers of heat from the plant. In SUNSTORE 4, 15,064 square metres (m^2) of solar collectors were installed and a 75,000 cubic metre (m^3) PTES was constructed, reaching the aim of increasing the solar fraction of the plant to 55 per cent of the thermal energy production, while focusing on sustainability, increased efficiency and low costs. In 2021, a new heat pump of two MW was installed to replace the old, inefficient one. The pump was planned for testing in mid-January 2022 and will double the efficiency in heating and cooling the thermal energy storage system, compared to the old one.[2]

Specific information about the solar thermal system	
SUNSTORE 1 (1996)	• 9,045 m^2 field consisting of arrays of 12.53 m^2 Arcon HT collectors (Collector field 1)
SUNSTORE 2 (2001- 2004)	• 8,019 m^2 field consisting of arrays of 12.53 m2 Arcon HT collectors (Collector field 2) Test collectors: • 103 m^2 Wagner roof integrated solar collectors - 881m^2 GJ ground placed flat plate solar collectors • 108 m^2 Thermosol Vacuum tube solar collectors • 211 m^2 IST concentrating solar collectors
SUNSTORE 4 (2012-2014)	• 15,064 m^2 field consisting of arrays of 13.88 m^2 Sunmark solar collectors (Collector field 3)
Other utilities	• 2,100 m^3 accumulation tank (SUNSTORE 1 & 2) • 75,000 m^3 water pit thermal storage

[2] Dansk Fjernvarme, 'New heat pump increases solar efficiency in Marstal', *Dansk Fjernvarme*, 30 December 2021.

	• 1,500 kW (produced heat) CO_2 heat pump (changed in 2022 for a 2 MW ammonia-based heat pump) • 4.15 MW wood chip boiler that runs an electricity producing Organic Rankine Cycle with a power of 750 kW

The long-term storage in Marstal is a pit thermal energy storage (PTES) with water as a storage medium. The storage is an upside-down, truncated pyramid upside down of 75,000 m^3. The excavated soil from the lower part of the storage system is used as an embankment around the storage. The storage system is covered by an onsite welded high-density polyethylene (HDPE) liner. On top of the storage the water is covered by a floating insulating cover. Charging and discharging of the storage is done through an inlet and outlet arrangement with three in/outlet pipes to the pit heat storage. The storage is charged to 80 to 85 °C during summer and discharged down to 10 °C during winter. The storage is used directly and as a heat source for the heat pump.[3]

Photo: Pit solar thermal under construction and half filled with water aerial view (source: PlanEnergi)

Investment and operation costs

The inhabitants of Marstal financed the original district heating network in the 1960s. Subsequently, the company financed the transition to solar by tapping into available subsidies and funding programmes. In the end, the total investment costs for the plant amounted to EUR 15.1 million, 35 per cent of which was covered by subsidies from an EU fund and the remainder of which was raised through Kommune Credit, a Danish funding programme that allows borrowing money at favourable rates.

[3] PlanEnergi, Summary technical description of the SUNSTORE 4 plant in Marstal, *PlanEnergi*, 1-2, accessed 19 April 2022.

Marstal District Heating uses a not-for-profit business model, which means that all potential profits are returned to the members in the form of lower energy prices. The project achieved cost targets of between EUR 30 and 60 / MWh for its various heat sources, with solar heat prices around EUR 30 / MWh.

The construction cost of the Marstal storage system was EUR 41 / m^3 of water (excluding VAT), including all pipe connections to the plant, the control system, geotechnical support, etc. The costs are cost-competitive compared to other storage systems (e.g. borehole, tank based) and if built today, there is the potential to bring costs down even further.

As the plant uses wood chips for cogeneration, prices became a burden in recent years, because the plant's main supplier has increased its prices.[4] With new Danish legislation that cuts electricity taxes on heat pumps in half, if Marstal District Heating implemented a project today it would have a more favourable economic situation if it opted for even more heat pump capacities.

Operational experiences and efficiency

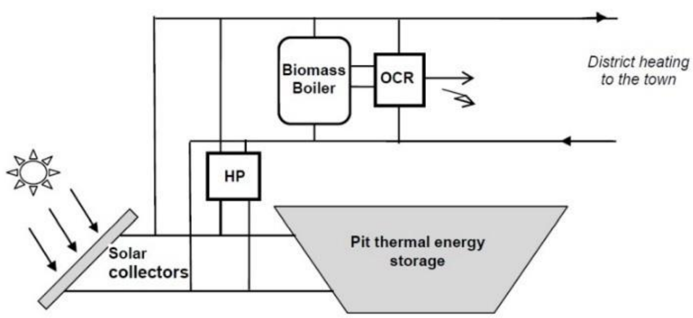

Figure 1: Configuration of the district heating system in Marstal (source: PlanEnergi)

Heat accumulation and storage in Marstal functions in a simple manner:

- In the summer, the solar system loads the storage and provides Marstal with district heating.
- Starting in the end of September, the stored heat has to be complemented with heat from the wood chip boiler or the heat pump. The boiler runs with an output of approximately 3.25 MW of heat and the integrated Organic Rankine Cycle will produce 750 kW of electricity. The heat pump runs when the electricity prices are low to cool the storage and heat up the return temperature to 75°C.
- In the winter, the back-up boilers will have to supply a few hours, and the heat pump also has to run when the electricity price is higher.
- In February, the solar system will begin to heat up the storage again.
- The wood chip boiler will run approximately full time until April.

[4] Eva Augsten, 'Denmark: 23 MWth Cover 55 % of Heat Demand of 1,500 Households', *Solarthermalworld*, 28 July 2014.

Marstal District Heating use storage systems (typically 110 or 160 litres) in the consumer substation installations. This allows low flow to load up the storages, low return temperatures and minimisation of pipes to the houses (and thus also reduced heat losses). The result is return temperatures of 33 °C in winter going up to 40 °C in summer. Forward temperatures are between 72 °C (summer) and 76 °C (winter).

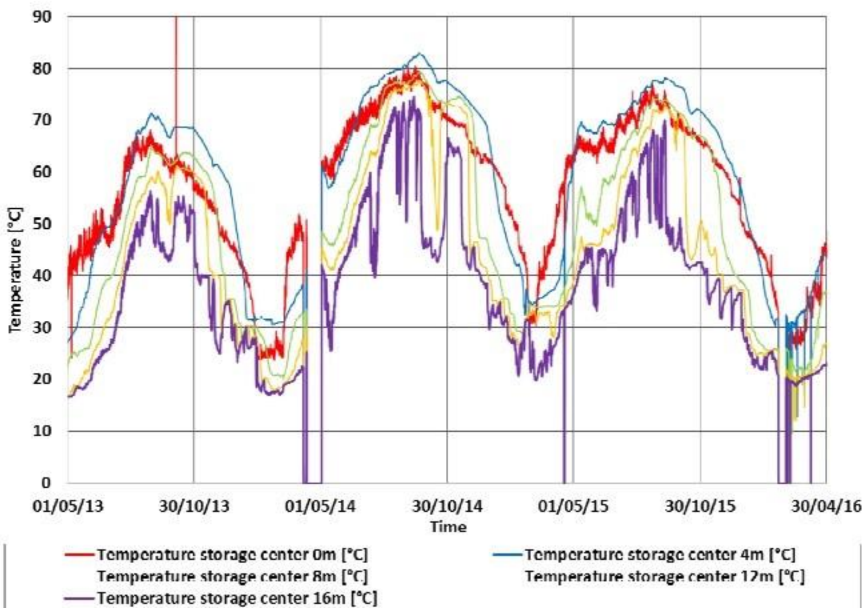

Figure 2: Trend of the water temperatures in the centre of the pit hat storage during the 3 years of monitoring period (source: Sunstore 4: CHP plant based on a hybrid biomass and large-scale solar system results after monitoring, A. Hammerschmid, LKjaegaard, I. Obernberger[5])

Monitoring of the process, which took place from May 2014 until April 2016, showed that the maximum temperature in the storage system was reached in the beginning of September (the peak was about 82 °C four metres below the surface in 2014). Until the end of October, the layers in the middle of the storage system could keep the temperatures quite constant as shown in Figure 2. The water temperature on top drops faster because of decreasing ambient temperatures and higher heat losses. Around March, the storage shows the lowest state of charge and the water temperatures are at minimum between 20 and 45 °C in all layers.[6]

The charging and discharging procedure of the pit heat storage is very dynamic in the summer period when no heat producer other than solar plant is in operation. All specifications, such as the 25-year service life, the maximum heat loss of 10 per cent and the 90 per cent recyclability have been verified by Lloyd's Register.[7]

[5] Alfred Hammerschmid, Lasse Kjaergaard Larsen, and Ingwald Obernberger, SUNSTORE 4: CHP Plant Based on a Hybrid Biomass and Large Scale Solar System - Results after Monitoring, *EUBCE*, 9 June 2016.

[6] Alfred Hammerschmid, Lasse Kjaergaard Larsen, and Ingwald Obernberger, SUNSTORE 4: CHP Plant Based on a Hybrid Biomass and Large Scale Solar System - Results after Monitoring.

[7] Robin Whitlock, 'Aalborg CSP receives certificate for its PTES technology from Lloyds Register', *Renewable Energy Magazine*, 31 May 2021.

Decision, design process and approaches applied

As the transition to solar-based heating in Marstal started almost two decades ago with the first pilots on the PTES, stakeholders had an early opportunity to gain understanding of the implemented technologies, which made it easier to reach consensus and make decisions.

Marstal District Heating is a consumer-owned cooperative. Daily decisions are taken by the board, which is elected at the yearly general assemblance. All major investments (the 8,000-m^2 plant, SUNSTORE 2 and SUNSTORE 4) have been discussed and decided by the general assemblance, where all consumers are invited. For example, the first project was decided with 144 votes for and 0 against. During the project preparation, the community is informed through articles in the local newspaper and through meeting members of the board or employees from the district heating company in their daily lives.

Summary and lessons learned

Marstal was not only the first place to establish a solar heating system, but also perhaps the first Danish city to gain international recognition for its efforts. Marstal's district heating system transformed from a traditional district heating plant to a solar heating and thermal storage pioneer, attracting today more than 2,000 to 3,000 visitors per year.

Besides being based 100 per cent on renewables, Marstal gained recognition for two decades of testing solar thermal pit storage. This is why some of the most valuable lessons learned are concerning technical solutions and their efficiency. These might be summarised as follows:

- An increase in the size of PTES can bring down the costs considerably. Denmark's first big (10,000 m^3) pit storage demonstration system in Marstal was nearly three times as expensive as today's biggest seasonal storage, which was put up in 2015 in Vojens and cost only EUR 24 / m^3. It is recommended to use a benchmark of around EUR 30 / m^3 when calculating the cost of pit heat storage with a capacity of 100,000 m^3 or more.
- Seasonal heat storage is a very cost-effective way to make use of surplus electric power generated by other renewable energy sources. For example, wind energy has already contributed up to 40 per cent on average to electricity generation in a year in Denmark[8] and it can have multiple benefits if this rich intermittent energy source is combined with seasonal storage via heat pumps.
- To reach higher efficiency, it is better to connect the seasonal storage to the district heating grid via a heat pump. This makes for lower storage temperatures throughout the year, which reduces heat losses.
- For production from a solar district heating plant, it is essential that the return temperature from the distribution network is low. A solution might be smaller storage systems in the consumer substation installations.

[8] This percentage is increasing, so for 2019 electricity generation from the wind counted for 47 per cent of the final consumption.

- To minimise excavation costs for preparing the storage system, the ground must consist of soils which can be excavated and handled by traditional methods and with no significant groundwater handling.
- To reduce heat loss into the air, the pit must be covered by insulation with guaranteed resistance to temperatures up to 90°C for the lifetime of the storage. The top insulation and the bottom membrane (in this case a 2.5 mm HDPE liner) are some of the most expensive parts in a PTES and the area of the insulation must consequently be minimised.
- Dry soils insulate better than moist or saturated soils, and moreover groundwater may introduce unwanted heat loss if heated groundwater flows across the site. Therefore, the groundwater level must be at a convenient depth below the bottom of the pit. Alternatively, a higher groundwater level is tolerated, but in that case no significant groundwater flow across the site is allowed.
- The loss of heat is reduced to a theoretical minimum when the pit has a spherical shape. The width must be minimised, for which reason the slopes of the sides of the pyramid must be as steep as is practically possible. This also reduces the surface area of the expensive top insulation.
- In the operational phase, the temperature in the soil adjacent to the storage system will increase, maybe up to 90°C close to the pit. This heating of the soil might cause a drying-up effect of the soil above the ground water table if no water is added from e.g. precipitation. In the actual case the clays seemed so pre-consolidated that the natural water content was considered to be close to the shrinkage limit.[9]
- Despite the use of automatic float vents, practical use of the pilot storage demonstrates that air pockets are formed below the floating roof foil containing up to several cubic metres of air, released when the storage is charged at the relatively high temperatures for this process. This is negative for the production, since there is no possibility of removing these air pockets. For the SUNSTORE 4 storage, vacuum vents and ventilation hoses made of HDPE material were used as more efficient solutions. They lead into ten inspection wells in which moisture in insulation can be surveyed and eventually pumped out and dried.

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[9] Dannemand Andersen J., Bodker L., and Jensen M.V., Large Thermal Energy Storage at Marstal District Heating, *GEO / PlanEnergi*, 3-4, 6 September 2013.