Solar Production from the Marstal Plant 1997-1999

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Abstract – In the autumn of 1996 a 8,034 m^2 solar district heating plant was erected by Marstal District Heating situated at the island of Ærø in Denmark. Since then the control system has picked up data information every 5 minutes concerning temperatures, flows, solar radiation and electricity consumption. The data are generated in 1-hour files in Excel and are presented and updated every hour at the internet address www.solarmarstal.dk/solarmarstal. The production from the solar collectors for 1997, 1998 and 1999 has been compared with TRNSYS-calculations using the monitored solar radiation and temperatures for the Marstal plant. TRNSYS calculations have been made with variable flow and with fixed flow. The comparison of calculated and monitored results will be presented and discussed using the detailed data picked up in the control system. It can be concluded that the production results from Marstal match the guarantees given by the manufacturer, that there are considerable advantages in using variable flow because of lower pumping costs and better possibilities of shutting down auxiliary boilers and finally that the use of TRNSYS-simulations of solar production from district heating systems give reliable results.

1. INTRODUCTION

In 1996 the world's largest heat producing solar plant was constructed to provide the Ærø situated town of Marstal with district heating. The plant included from the start 8,038 m^2 solar collectors, which in 1999 was expanded to 9043 m^2, and covers 12-15% of the district heating needs of the town, which was then new in Denmark. The solar plant is equipped with variable-speed solar collector pumps in order that a desired fixed outlet temperature may be obtained from the solar collectors.

The plant has now been in function for three years. A parallel action has been the measuring programme which has registered a long series of parameters. At the conclusion of the measuring programme a report was published, "Measuring programme for solar heat plant in Marstal District Heating " (in Danish) (Marstal District Heating et al, 2000) in which the 1997, 1998 and 1999 output and experiences of the plant are summed up and analysed. The present paper is based on this report.

From the start the control system has picked up data information every 5 minutes concerning temperatures, flows, solar radiation and electricity consumption. The data are generated in 1-hour files in Excel and are presented and updated every hour at the internet address www.solarmarstal.dk/solarmarstal.

The production of the solar collectors has been compared with TRNSYS-calculations using the monitored solar radiation and temperatures for the Marstal plant. TRNSYS calculations have been made with variable flow and with fixed flow. The comparison of calculated and monitored results will be presented and discussed using the detailed data picked up in the control system.

2. MEASURING RESULTS

2.1 Overall description of the energy system.
Until 1996 Marstal District Heating received its heat solely from a heating central heated only with waste oil. In 1996, however, a new solar heat plant was installed. The solar plant is connected to the old heating central through a 700 m long transmission pipe.

The initial solar heating plant had 8,038 m^2 and the storage tank had 2,100 m^3. Furthermore an emergency generator was established, diesel powered. In April 1999 a further 1,005 m^2 of solar collectors were added.

In 1999 a storage with earth pipes has been established and in 2000 a heat pump. Neither the earth pipe storage nor the heat pump is included in the present measuring programme.

Compared to former plants the control of the solar collectors is special because a variable flow is implied. Because of that, a steady outlet temperature from the solar collectors can be maintained. Under normal circumstances the solar collector flow is fixed and the outlet temperature varies. The advantage of keeping a fixed outlet temperature is partly a reduced consumption of electricity for the pumps and partly the possibility of turning off the boilers of the district heating plant because the production of the solar heat plant may be fixed at the temperature chosen for the district heating net.

The pumps of the primary side of the solar heating plant will start as soon as there is a theoretical chance of gaining anything compared to the temperature in the bottom of the storage tank. The control will introduce the temperature of the storage tank as the solar collector's temperature in the equation of the solar collector. When the external temperature and the incoming solar energy have reached a size that gives a positive expression, the first pump will start. The pumps on the secondary side will start when the external temperature exceeds the temperature in the bottom of the storage tank by 2^{o} C. Following that, the pump flow of the primary and secondary sides are regulated to obtain the pre-set temperature level.

The pump flow may be regulated between 15 and 100% of the maximum output (between 0,034 l/min and 0,35 l/min). Provided the temperature of the heat exchangers is higher than the chosen pre-set temperature level, part of the output will go directly to the district heat system and part of it will go through the storage tank, allowing it to be heated from the top.

An outlet temperature for the district heating system is fixed, too (normally of 72^{o} C). In case this temperature is exceeded, the desired outlet temperature will be obtained by mixing with return flow from the district heating system.

The storage tank will be discharged if the outlet temperature from the heat exchangers is below the pre-set temperature level.

2.2 Production results for 1997, 1998 and 1999

In the following tables the production is added up for the first three years of solar heat.

1997	Boiler and generator MWh	Solar collectors MWh	Total MWh	Degree of coverage, solar coll. %	Replace-ment of oil, Litres
JAN	4,511.0	32.9	4,543.9	0.72	3,520
FEB	3,198.0	104.2	3,302.2	3.16	11,149
MAR	2,789.6	334.2	3,123.8	10.70	35,759
APR	2,219.1	405.4	2,624.5	15.45	43,378
MAY	1,212.2	475.3	1,687.5	28.17	50,857
JUN	248.7	567.0	815.7	69.51	60,669
JUL	126.0	563.1	689.1	81.72	60,252
AUG	-	567.0	567.0	100.00	60,669
SEP	519.8	375.6	895.4	41.95	40,189
OCT	1,772.3	216.9	1,989.2	10.90	23,208
NOV	3,357.0	63.6	3,420.6	1.86	6,805
DEC	3,427.1	11.2	3,438.3	0.33	1,198
Total	23,380.8	3,716.4	27,097.2	13.72	397,655

Table 2.1 Measured production, 1997

1998	Boiler and generator MWh	Solar collectors MWh	Total MWh	Degree of coverage, solar coll. %	Replace-ment of oil, Litres
JAN	3,725.3	58.0	3,783.3	1.53	6,206
FEB	3,162.0	60.5	3,222.5	1.88	6,474
MAR	2,852.9	395.3	3,248.2	12.17	42,297
APR	2,250.9	273.2	2,524.1	10.82	29,232
MAY	668.4	578.3	1,246.7	46.39	61,878
JUN	419.5	448.4	867.9	51.66	47,979
JUL	436.6	462.3	898.9	51.43	49,466
AUG	397.6	470.3	867.9	54.19	50,322
SEP	874.6	220.1	1,094.7	20.11	23,551
OCT	2,061.8	184.8	2,246.6	8.23	19,774
NOV	3,422.3	54.3	3,476.6	1.56	5,810
DEC	4,175.3	21.4	4,196.7	0.51	2,290
Total	24,447.2	3,226.9	27,674.1	11.66	345,278

Table 2.2 Measured production, 1998

1999	Boiler and generator MWh	Solar collectors MWh	Total MWh	Degree of coverage, solar coll. %	Replace-ment of oil, Litres
JAN	4,004.0	22.1	4,026.1	0.55	2,365
FEB	3,670.9	89.5	3,760.4	2.38	9,577
MAR	3,328.4	207.2	3,535.6	5.86	22,170
APR	1,861.5	455.5	2,317.0	19.66	48,739
MAY	860.9	608.8	1,469.7	41.42	65,142
JUN	439.9	470.8	910.7	51.70	50,376
JUL	38.9	663.3	702.2	94.46	70,973
AUG	193.4	518.1	711.5	72.82	55,437
SEP	258.2	438.7	696.9	62.95	46,941
OCT	1,576.2	288.8	1,865.0	15.49	30,902
NOV	2,830.6	53.7	2,884.3	1.86	5,746
DEC	3,747.1	22.4	3,769.5	0.59	2,397
Total	22,810.0	3,838.9	26,648.9	14.41	410,762

Table 2.3 Measured production, 1999

The first column shows the production by boilers and generators. As will be seen, it has been possible to turn off the boilers for the whole month of August 1997. More than that, the boilers have been turned off for shorter periods during the summer months. The second column shows the measured solar heat production after the heat exchangers. After that, the solar heat coverage has been calculated in percentage and the solar heat contribution has been converted into amount of oil saved.

On the 15 of April 1999 a further 1,005 m2 of solar collectors were put into use. In the 1999 table the production in the last column has been converted to correspond to 8.038 m2 all year round.

The complete annual solar heat production is shown in table 2.4

1997	462 kWh/m^2
1998	401 kWh/m^2
1999	432 kWh/m^2
Average	432 kWh/m^2

Table 2.4 Production per m^2.

The original production level of the solar collectors was calculated at 3250 MWh/year or 404 kWh/m^2. However, the incoming solar energy at Marstal is higher than for the normal year explaining the higher average production.

2.3 Method for data presentation

The internet data presentation is based on the 5 minute files, generated constantly by Marstal District Heating control system.

The treatment of the data is carried out in the Excel spreadsheet programme. Once every hour the five minute file is copied to Excel which will then calculate the last hour's production of:

a. Solar radiation (MWh)
b. Solar collector production (secondary side of heat exchanger) (MWh)
c. Production from the CHP unit (MWh)
d. Production from oil boiler in heat plant (MWh)
e. Total district heating production (MWh)
f. Production in and out of storage tank (MWh)
g. Energy contents in storage tank (MWh)
h. Production from earth pipe storage and heat pump plant (MWh)
i. Electricity consumption, primary solar collector pumps
j. Electricity consumption, secondary solar collector pumps (kWh)

The hourly average for the following temperatures are calculated as well:
k. Ambient temperature (^{o}C)
l. Storage tank temperature, top (^{o}C)
m. Storage tank temperature , bottom (^{o}C)
n. Temperature into solar collector (^{o}C)
o. Temperature out of solar collectors (^{o}C)
p. Forward temperature, district heating system (^{o}C)
q. Return temperature, district heating system (^{o}C)

After that, the above data are saved in a data file which contains hour values for the present year.

Based on the data file, a number of graphs and tables are generated.

Graphs:

Two graphs showing the hourly values for the last 25 hours:

G1 (temperatures):
k. Ambient temperature (^{o}C)
o. Temperature out of solar collectors (^{o}C)
p. Forward temperature, district heating system (^{o}C)

G2 (production):
a: Solar radiation (MWh)
b: Solar collector production (MWh)
e: Total district heating production (MWh)

Two graphs (G3 and G4) showing the 24 hour values for the last month:

G3 (temperatures):
k. Ambient temperature (^{o}C)
l. Storage tank temperature, top (^{o}C)
m. Storage tank temperature, bottom (^{o}C)

G4 (production):
a: Solar radiation (MWh)
b: Solar collector production (MWh)
e: Total district heating production (MWh)

Two graphs (G5 and G6) showing the monthly values for the last year:

G5 (temperature):
k. Ambient temperature (^{o}C)
l. Storage tank temperature, top (^{o}C)
m. Storage tank temperature, bottom (^{o}C)

G6 (production):
a: Solar radiation (MWh)
b: Solar collector production (MWh)
e: Total district heating production (MWh)

Tables:

Three tables are produced which each contain the following points:

a: Solar radiation (MWh)
b: Solar collector production (MWh)
e: Total district heating production (MWh)

i: Electricity consumption, primary solar collector pumps (kWh)

T1 is a monthly table which shows the 24 hour values
T2 is a yearly table which contains the monthly values
T3 contains the annual values.

Once every hour G1 and G2 are updated. Once every 24 hours G3, G4 and T1 are updated. Once every month G5, G6 and T2 are updated. At the same time the values of the previous month are saved. Once a year T3 is updated and last year's values are saved.

Since a lack of data may occur during a period, inconsistencies may occur between the tables produced and the actual meter reading. A correction of this will be attended to in the spring of 2000.

2.4 Comparison using the TRNSYS-running.
In order to give a feeling of how close the TRNSYS-calculations are to the actual measurements and in order to attempt an explanation the effect of various control strategies, the measurement results have been compared with calculations of the simulation programme TRNSYS. The input data are the measured hourly values for solar radiation, ambient temperatures etc. in Marstal. The solar radiation is measured by 4 different solar meters. The largest and the lowest measured values are discarded and the average of the remaining two entered in the calculations. A calculation has been carried out for the variable flow (i.e. a fixed outlet temperature) as well as for the constant flow (and hence the variating outlet temperature). In the following the calculated results have been compared with the measured results.

1997	Meas-ured	Calculated			
		Var. flow	%	Fixed flow	%
Jan	0	0	0	0	0
Feb	104	86	82	102	98
Mar	334	254	76	301	90
Apr	410	358	87	417	102
May	470	426	91	509	108
Jun	567	563	99	581	102
Jul	563	567	101	581	103
Aug	567	613	108	593	105
Sep	376	363	97	411	109
Oct	217	195	90	223	103
Nov	64	54	85	62	97
Dec	11	8	70	9	84
Sum	3684	3485	95	3790	103

Table 2.5 Calculated output compared with measured output 1997

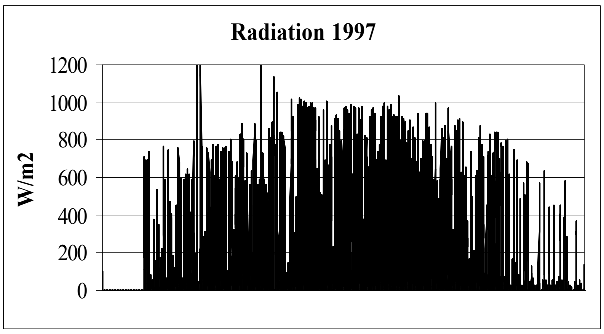
1998	Meas-ured	Calculated			
		Var. flow	%	Fixed flow	%
Jan	57	38	66	45	78
Feb	61	39	65	51	84
Mar	395	326	83	374	95
Apr	275	224	82	267	97
May	578	529	91	600	104
Jun	449	400	89	448	100
Jul	462	390	84	443	96
Aug	470	383	81	436	93
Sep	221	174	79	208	94
Oct	184	142	77	166	90
Nov	54	37	67	42	77
Dec	21	16	76	20	92
Sum	3227	2697	84	3099	96

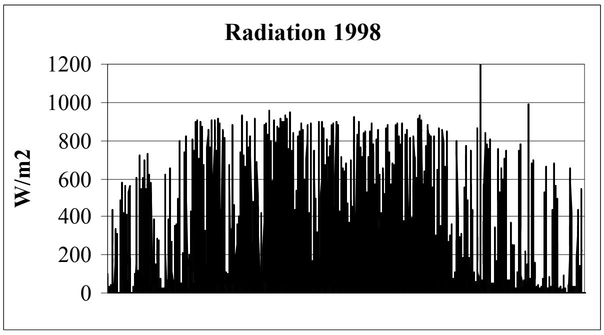
Table 2.6 Calculated output compared with measured output 1998

1999	Meas-ured	Calculated			
		Var. Flow	%	Fixed flow	%
Jan	22	17	76	20	90
Feb	90	72	80	86	97
Mar	207	199	96	234	113
Apr	456	409	90	462	101
May	609	533	88	597	98
Jun	471	375	80	425	90
Jul	664	618	93	610	92
Aug	518	534	103	531	102
Sep	439	393	90	412	94
Oct	289	244	85	276	96
Nov	54	60	112	69	128
Dec	22	20	89	24	108
Sum	3839	3475	91	3745	98

Table 2.7 Calculated output compared with measured output 1999.

The measured results for 1998 are considerably above the calculated result with a variable flow. The measured solar radiation for 1997, 1998 and 1999, however, looks like this:





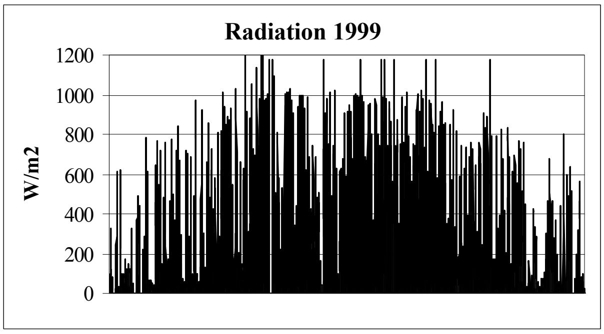
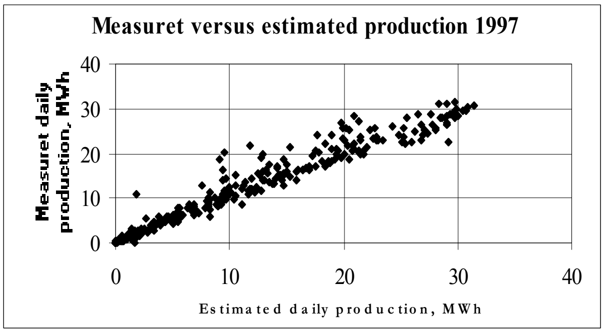
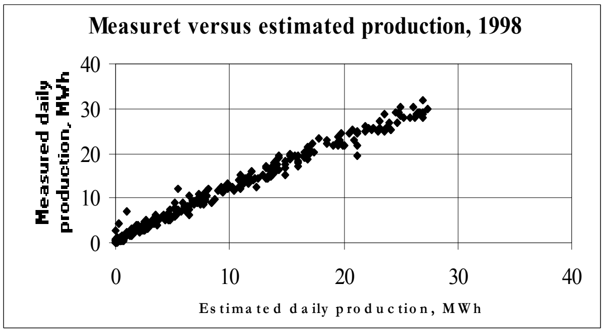


Figure 2.1. Hourly values for measured solar radiation 1997, 1998 and 1999.

As will be seen, the solar radiation in 1998 does not exceed 900 W/m^2, which indicates that the solar radiation has not been correctly measured. When the 24 hour values for measured output are compared with the calculated output, the following figure appears:





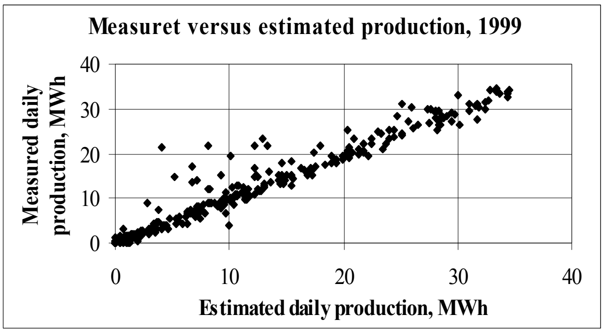


Figure 2.2. 24 hour values for measured output compared with calculated output (variable flow) 1997, 1998 and 1999.

I 1997 and 1999 the agreement between measured and calculated outputs is good. There are, however, a number of days where the measured output is higher than the calculated output, presumably due to a lack of data. In 1998, however, the measured output is systematically higher than the calculated output, which would occur when the actual solar radiation is higher than the measured solar energy.

Marstal District Heating has changed one of the four solar meters round New Year 1998-1999 which may be the reason for the measurements to become more correct in 1999. Under all circumstances, however, it must be stated that the measurement of solar radiation has been uncertain and the measurements for the main part of 1998 give a value that is too low.

The outlet temperature was set at app. 70^{o}C in 1997, whereas the pre-set temperatures have been gradually raised in spring and decreased in autumn since autumn of 1997. In this way the solar collectors will produce at lower temperatures and thus give a better output.

Data dropout

Particularly in 1999 there have been data dropouts lasting more than one day. The computer will try and repair this by using data before and after, in order that the final result should not be different. Lack of agreement between the measured data and the calculated data may, however, be caused by date dropouts.

Difference between variable and fixed flow.

During the spring and autumn months the calculation for fixed flow are considerably closer to the measured values than the calculations for variable flow. This is owed to the Marstal plant being run in a way that allows even the low temperatures in the solar collectors to be used in spring and autumn periods. When calculating the variable flow, however, the pre-set temperature level is constant. For some of the summer months (August 1997, July 1998 and August 1999) the calculated output is larger with the variable flow than with the fixed flow. The reason is that a better stratification is obtained in the heat storage with a variable flow since the only temperature input is added from the top. This makes the solar collectors function at a lower temperature than when using fixed flow.

During long periods with much sunshine, like August 1997 and end of July, beginning August 1999, the heat storage will be filled completely with hot water with the same temperature as the pre-set temperature level, after which the outlet temperature to the solar collectors will rise considerably. The capacity of the storage may be increased by raising the pre-set temperature level, but even that may be too little. In August 1997, the solar radiation was so strong that 25 MWh had to be cooled off by running the solar collector pumps at night.

Production in a normal year (TRY)
In table 2.8 the production has been calculated for the normal year.

	Production MWh
January	12
February	102
March	168
April	407
May	471
June	607
July	501
August	484
September	289
October	155
November	33
December	10
Total	3237

Table 2.8 TRNSYS production, normal year (TRY)

The total of 3237 agrees with the original estimate of 3250 MWh/year.

2.5 Savings when using variable flow
Consumption for the solar collector pumps has been measured from mid April 1999. On the 31.12.1999 the total consumption was

Pump	Electricity consumption kWh	Solar collectors prod. MWh	kWh/ MWh
Primary pumps	6.799	3.292	2,1
Secondary pumps	7.552	3.292	2,3
Total	14.331	3.292	4,4

Table 2.9 Electricity consumption, solar collector pumps.

The electricity consumption of 4,4 kWh per MWh heat produced is as expected. In a solar heat plant using fixed flow, the electricity consumption will be 3-4 times higher. In Ry heating plant, for example, the electricity consumption for the solar collector pumps is 16-20 kWh per MWh heat produced.

Using TRNSYS a calculation has been carried out of the number of hours the boilers may be stopped when using either fixed flow or variable flow. The results are shown referring to different demands for an average output from the boilers.

Output MW	1997		1998		1999	
	Fixed	Var.	Fixed	Var.	Fixed	Var.
0	1429	1565	18	172	616	777
0,028	1643	1695	18	172	784	845
0,278	1669	1861	18	172	806	1060

Table 2.10 Number of hours with a boiler stop

A missing output of 28 kW will mean that the outlet temperature falls close to 1 ^{o}C which is fully acceptable. As will be seen, it is possible to stop the boilers for another couple of hundred hours provided variable flow is used.

3. DISSEMINATION

Marstal District Heating puts a great effort into disseminating results from the plant. An example is that the plant receives app. 4000 annual visitors, out of which quite a few district heating companies. Outside of Ærø Marstal District Heating presents its results through 10-15 annual lectures for district heating companies, consultants and researchers.

An improved dissemination has been included in this project concerning two areas: 1) Presenting the measurement results in the web site of Marstal District heating and 2) Visualising the results for the visitors to the solar heat plant.

3.1 The internet presentation
As described earlier, the data are collected and treated once every hour. This generating of data is terminated by the ftp system built into the control system of the computer calling the Marstal District Heating internet provider to transfer the generated hour values, graphs and tables to the homepage
www.solarmarstal.dk/solarmarstal.

3.2 Visualising at Marstal District Heating
Visitors to the solar heat plant have access to a computer screen where they have a choice of 10 different screen pictures which describe the actual output, for example.

4. CONCLUSIONS

Summing up the following may be concluded:

The solar heat plant output is as expected, as the plant has given an annual output of 432 kWh/m^2 as compared to the promised 404 kWh/m^2 in a normal year. However, the solar radiation at Marstal exceeds that of the normal year, wherefore calculations have also been carried out on the output. The calculation shows an output of 403 kWh/m^2 in a normal year.

The running of the solar heat plant is very close to being optimal, as a variable flow is used during the summer months along with a fixed temperature from the solar collectors corresponding to the desired outlet temperature in the district heating system. The desired outlet temperature is decreased to allow the output to approach that of the fixed flow. The output may possibly be raised a little during the spring and autumn months provided the desired outlet temperature from the solar collectors is reduced.

Using the TRNSYS for simulating and calculating the output and performance of the solar heat plant results in good agreement with the actual production. Differences may, however, occur, especially when the comparisons are carried out by the hour or day by day. This may be due to data dropouts.

The saving incurred in the electricity consumption by using variable flow instead of fixed flow is app. 75% or 50 MWh/year. The boilers may be stopped an extra couple of hundred hours because the solar collectors produce warm water at the desired outlet temperature.

There have been very few problems connected to running the solar heat plant. Largely spoken, it has been functioning since the start. Maintenance has been limited to the changing of three solar collector glass panes and birth aid to the sheep that keep the grass down around the plant.

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