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SUNSTORE 4: CHP PLANT BASED ON A HYBRID BIOMASS AND LARGE SCALE SOLAR SYSTEM – RESULTS AFTER MONITORING

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ABSTRACT: To increase the share of renewable energies in district heating systems is a key issue to reach the environmental targets within 2030. In this context especially biomass and solar thermal energy are the main renewable sources to achieve these goals. In the past the combined use of biomass and solar for district heat production was considered as an economic competition. In the meanwhile it turned out that for medium and large scale applications the advantages of both can be integrated successfully into systems but creates technical and economic challenges to be solved. Within the European project "SUNSTORE 4" a large-scale district heating system based on hybrid solar in combination with a biomass CHP unit has been demonstrated in Marstal-Denmark and a 3 year monitoring period was performed. The new facility in Marstal consists of a 15,000 m^2 solar system, a biomass CHP plant based on a thermal boiler, an ORC with 3.2 MW heat and 750 kW$_{el}$ electric output and a flue gas condensation with 1.1 MW$_{th}$, a 75,000 m^3 pit heat storage and a 1.5 MW$_{th}$ heat pump with CO_2 as refrigerant. All units have been tested and evaluated successfully and the expected design parameters can be clearly achieved.
Keywords: biomass, cogeneration, demonstration, monitoring, organic rankine cycle, storage.

1 INTRODUCTION AND OBJECTIVES

For a 100% renewable energy supply for district heating systems or similar large-scale heating systems with solar energy as a main energy source, a number of challenges and barriers exists. It is obvious that for such applications a long-term heat storage and an intelligent energy management system have to be established in order to achieve a significant solar fraction. The solar energy production capacity and the heat storage capacity have to increase with decreasing annual solar radiation (the challenge in Northern European countries is considerably higher).

Within the European demonstration project "SUNSTORE 4" (project duration from mid of 2010 until mid of 2014) an innovative, multi-applicable and cost efficient large-scale district heating system based on hybrid solar and biomass with a long-term heat storage and an Organic Rankine Cycle (ORC) for green electricity production was erected and put in operation mid of 2012. The plant is located in Marstal on the Island of Aero in Denmark.

The SUNSTORE 4 project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no ENER/FP7EN/249800. The whole consortium of the project and the role of each partner is shown in Table I.

Table I: Project consortium of SUNSTORE 4

Partner name	Country	Main task
Marstal Fjernvarme a.m.b.a.	DK	project coordinator and plant erector/operator; dissemination northern/western Europe
SUNMARK A/S	DK	supplier of solar collectors
Euro Therm A/S	DK	supplier of biomass boiler system
Advansor	DK	supplier of heat pump
Steinbeis Innovation GmbH	D	long term monitoring
Energy Management AB	S	european level concept study
BIOS BIOENERGIE-SYSTEME GmbH	A	engineering of ORC and thermal oil system; optimisation of biomass boiler (CFD)
Euroheat & Power	B	dissemination European level
CityPlan spol. s r.o.	CZ	dissemination eastern Europe
Ambiente Italia	I	dissemination southern Europe
PlanEnergi	DK	technical consultant

In order to get a deep insight and understanding of the system and component behaviour as well as to optimize the whole system, its control strategy and the components, comprehensive measurements and a long-term monitoring for 3 years has been performed.

2 APPROACH

In the year 2010 the existing district heating system in Marstal consisted of an 18,300 m² solar field, a 10,000 m³ pit heat storage and of several bio-oil boilers for peak load coverage (total thermal capacity 18.3 MW$_{th)}$ in winter. In the past about 25% of the annual heat demand were covered by the solar plant. In order to increase the solar production and to substitute the costly bio-oil heat production by heat production from solid biomass, the new SUNSTORE 4 system was designed. Within the new project a large-scale solar field with a long-term pit heat storage was integrated. The second main renewable heat source is a biomass CHP plant based on an ORC which is fired with wood chips. In order to increase the efficiency and to reduce the specific costs of the solar system a compressor driven heat pump using CO_2 as refrigerant forms a part of the heat production system.

The large-scale district heating system with a heat demand of about 32,000 MWh/a is now supplied based on a balanced ratio of solar and biomass energy. The new plant consists of a 15,000 m^2 solar system, a biomass CHP plant based on a thermal oil boiler, an ORC with 3.2 MW heat and 750 kW$_{el}$ electric output and a flue gas condensation with 1.1 MW$_{th}$, a 75,000 m^3 pit heat storage and a 1.5 MW$_{th}$ heat pump with CO_2 as refrigerant. Figure 1 shows an overview of the former existing plant units as well as of the new plant units constructed within the SUNSTORE 4 project.

The biomass system manages the differences between the overall heat demand and the solar production mainly from autumn to spring whereas the operation of the heat pump takes place mainly at the end of the winter season in order to optimize the solar efficiency and the solar yields.

The overall hydronic system (see Figure 2) is separated by a heat exchanger into the district heating circuit (integration of the biomass system with the ORC) and the solar/storage circuit (integration of the solar and the heat storage system) whereas the solar system itself has a further closed water/glycol loop. The heat pump is integrated in parallel to this heat exchanger (i.e. the condenser side will be part of the district heating circuit and the evaporator side will be part of the solar/ storage circuit).

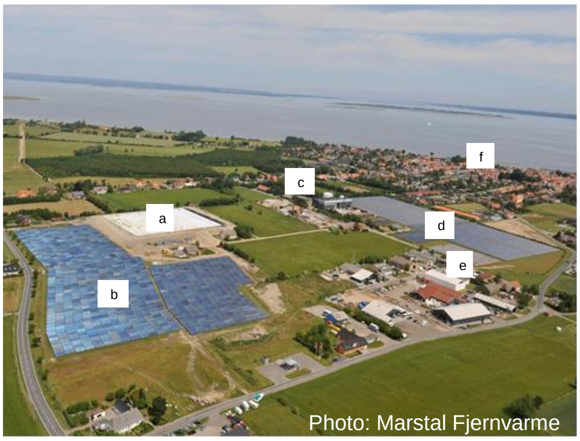

Figure 1: Plant overview of SUNSTORE 4
Explanations:
- a) 75,000 m³ pit heat storage
- b) 15,000 m² solar plant
- c) Central station (biomass-CHP / heat pump)
- d) 18,300 m² solar plant (existing since 1996/2003)
- e) 10,000 m³ pit heat storage (existing since 2003)
- f) bio-oil boilers

The aim of the measurement and monitoring period was to derive improvements for the system design and to demonstrate the efficiency and the feasibility of the plant based on long-term monitoring results.

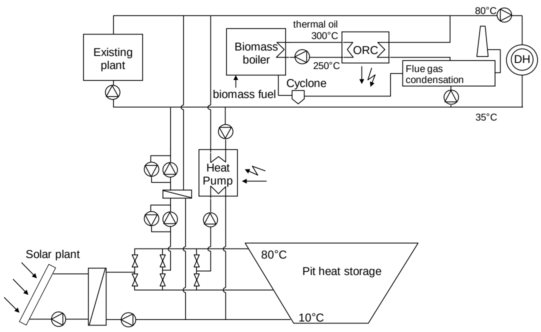

Figure 2: Principle hydronic system of SUNSTORE 4

3 INNOVATION AND METHODOLOGY

The main innovation of this project is the system integration and optimized interaction of the solar panels, the heat pump, the biomass CHP plant and the long-term pit heat storage. Especially the technical and functional reliability of the long-term heat storage is of big importance in order to avoid problems with the liners and the cover (the high solar fraction means high temperatures in 4-5 summer months in the storage and thus the influences on the lifetime of plastic liners have to be considered).

Already at an early stage of the design phase the measuring and data evaluation programme and the sensor placing plan were defined in order to achieve a high quality and efficient plant monitoring.

The objective of the measurements was to get the knowledge of the dynamic and transient interaction of the sub-systems (as input for system optimization) and on the other hand to achieve mid and long-term energy balances. The following parameters were measured and monitored:

- Efficiency and energy balance of the solar collector field, of the biomass boiler and of the ORC unit;
- Complete mass and energy balances and emissions from the biomass boiler plant within a dedicated one week test-run with accompanying measurements and analyses
- COP and energy balance of the heat pump
- Temperatures, stored energy, energy balance and heat loss rates of the large-scale heat storage system.

Furthermore, all relevant economic parameters were recorded during the monitoring phase in order to calculate the heat production costs of the individual components and of the entire system.

4 MONITORING RESULTS AFTER THREE YEARS OF OPERATION

The construction of the SUNSTORE 4 project took place between autumn 2011 and mid of 2012. After start-up in autumn 2012 the plant was in operation in a test and demo mode for about one year (until mid of 2013) in order to obtain maximum information on the behavior and interaction of sub-systems and the system as a whole in as many as possible operation modes. It was the aim to obtain the full component characteristics by transient measurements in order to evaluate and verify the initial design assumptions. After this first demo period a dedicated monitoring period of all new plant units was performed within a period of 3 years from 01st of May 2013 until 30th of April 2016 and the results are shown in the following chapters. All data used are originated by the local SCADA system at the plant and are based on hourly average values.

4.1 Heat pump

The compressor driven heat pump with a nominal heat output of 1.5 MW_{th} and using CO_2 as refrigerant (see photograph in Figure 3) is mainly operated from the end of the year until the end of March and for some hours in May of each year and additionally for the optimization of the solar efficiency and the solar yields.

For the operation of the heat pump also the specific electricity prices (in Denmark special prices for the operation of heat pumps are valid) in different periods have to be considered in order to produce the heat output from the heat pump in an efficient way.

Due to the intelligent integration of the heat pump into the overall hydronic system according to Figure 2 the evaporator side of the heat pump is able to utilize low temperature energy from the bottom of the heat storage and reduces the temperature there to below 20°C whereas the condenser side of the heat pump heats up the return of the district heating network from about 35°C up to 75°C. With this integration of the heat pump the heat capacity of the heat storage can be increased due to the larger temperature difference, the efficiency of the solar system can be increased due to the lower temperatures of the inlet that comes from the bottom of the heat storage and the heat losses from the heat storage get reduced due to the lower average temperature.

Figure 3: Picture of the compressor driven heat pump

Figure 4 shows the trend of the thermal capacities of the heat pump, i.e. the thermal input from the storage (evaporator side of the heat pump) and the thermal output to the district heating (condenser side of the heat pump).

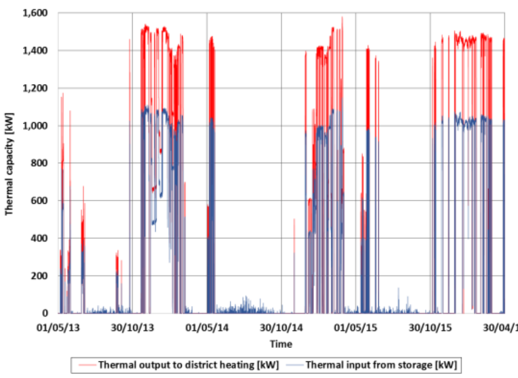

Figure 4: Trend of the thermal capacities of the heat pump during the 3 years monitoring period

Within the dedicated 3 years monitoring period the average annual amount of thermal energy delivered from the storage to the heat pump amounted to about 1,900 MWh/a and the thermal energy delivered to the district heating system amounted to 2,800 MWh/a. The resulting electricity consumption of the heat pump was 900 MWh/a and the coefficient of performance (COP = heat delivered/electricity consumption) achieved was 3.12 on average. The project target for the COP of the heat pump was 3.1 and could be reached within the 3 years period.

Figure 5 shows the trend of water temperatures on the input and output side of the heat pump. The temperatures at the district heating side are quite constant (inlet temperature between 35-40°C and outlet temperature about 74°C) when the heat pump is in operation. The temperatures at the heat source side (pit heat storage) have a higher variation during the operation time (inlet temperature between 30-50°C and outlet temperature about 20-30°C). During start-up and fast load changes of the heat pump the hydronic system supplies partly too high water temperatures (originating from the solar plant) to the evaporator due to not perfectly balanced water flows in the system. In the summer season when the heat pump is not in operation the measurement of the outlet temperature of the evaporator shows very high values which seems to have its origin in an uncontrolled circulation. The improvement of those operation periods will be part of the further optimization program.

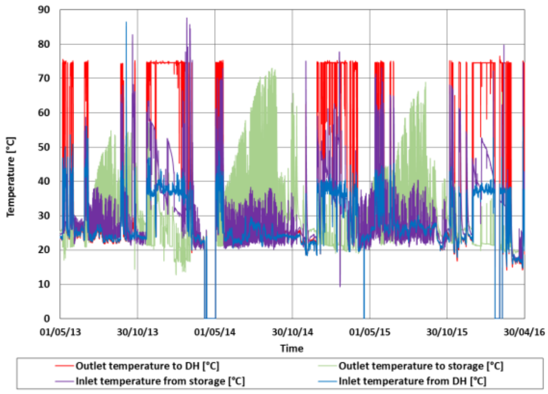

Figure 5: Trend of the temperatures on the input and output side of the heat pump during the 3 years monitoring period

4.2 Biomass CHP plant based on an ORC

The heat producers within the biomass CHP plant are the ORC condenser (nominal capacity 3.2 MW), the flue gas condensation unit (nominal capacity 1.1 MW) and the grate cooling (nominal capacity 130 kW). In Figure 6 pictures from the biomass-fired thermal oil boiler and the ORC unit can be seen.

The flue gas condensation unit and the ORC condenser are connected in serial in order to reach a high efficiency for both systems. In this way the supply temperature of the flue gas condensation unit can be kept very low and the electric efficiency of the ORC is mainly defined by the relatively low district heating supply temperature of up to 80°C.

The biomass combustion plant is connected with the ORC system via a thermal oil circuit consisting of the thermal oil boiler, the thermal oil economizers and the corresponding thermal oil loop including all relevant safety devices. Within the flue gas stream between the thermal oil economizers and the flue gas condensation unit an air pre-heater is placed in order to pre-heat the combustion air.

In periods where the ORC is not in operation the heat produced from the thermal oil boiler (incl. thermal oil economizers) can be directly transferred to the district heating system via the high temperature thermal oil / water heat exchanger (TO HT-HX) and the low temperature thermal oil / water heat exchanger (TO LT-HX) and thus are by-passing the ORC which was designed as split system (using high and low temperature energy from the flue gases of the biomass system).

Figure 6: Picture of the thermal oil boiler (above) and the ORC unit (below)

Figure 7 shows the trend of the thermal outputs of the different heat production units of the biomass CHP plant. The plant is operating between 80-100% of its nominal load from October until end of April. During summer the plant is stopped. Most of the time the grate cooling, the flue gas condensation and the ORC are producing heat in parallel while the time the thermal oil / water heat exchangers are in operation is very limited. Thus, the performance and the availability of the biomass CHP plant is high. The average annual thermal energy produced from the biomass system to the district heating amounted to about 16,100 MWh/a. within the 3 years monitoring period.

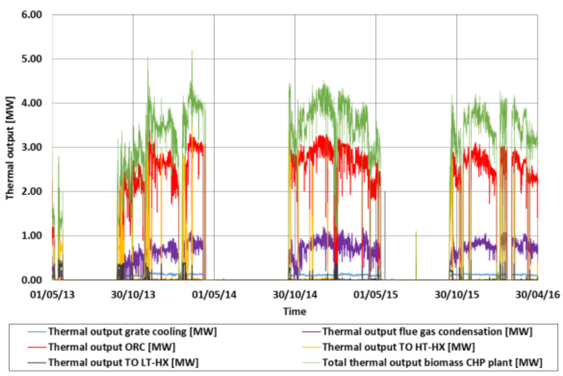

Figure 7: Trend of the thermal outputs of the biomass CHP plant during the 3 years monitoring period

In the course of a dedicated 3 days test-run in the beginning of December 2013 complete mass and energy balances as well as emissions from the biomass boiler plant with accompanying measurements and analyses were performed by BIOS BIOENERGIESYSTEME GmbH performed as a basis for further optimization activities.

The results of the measurements and calculations performed during this test-run showed a boiler efficiency between 87-88% (furnace incl. air pre-heater). Including the energy recovery of the condenser the efficiency raises to 103 to 104% (based on NCV). The project target for the boiler efficiency including the flue gas condensation unit was >100% and could be clearly reached within the test run.

It could be also evaluated that the temperatures in the combustion chamber of the biomass furnace have been closed to 1,100°C. These relatively high temperatures indicated that the flue gas recirculation ratio was too low for the fuel used (wood chips with a water content of approx. 27%). Recommendations for the improvement of the flue gas recirculation and the furnace control system were implemented by the plant operator in 2014.

Figure 8 shows the performance of the ORC electric production. Within the 3 years monitoring period the gross electric production amounted to 2,635 MWh/a in average and the electric own consumption amounted to 138 MWh/a. The resulting net electric production was 2,497 MWh/a and the gross electric efficiency achieved was 19.3%. The project target for the gross electric efficiency of the ORC was 18% and could be clearly exceeded within the 3 years period.

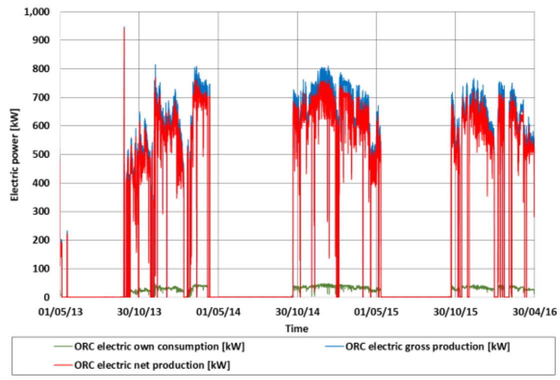

Figure 8: Trend of the electric power production and electric own consumption of the ORC during the 3 years monitoring period

4.3 Pit heat storage:

The monitoring of the 75,000 m³ pit heat storage with a floating insulation on top consisted mainly of the measurements of temperatures and energy flows (charging and discharging).

Figure 9 shows the pit heat storage before filling with water and Figure 10 shows a cross section of the storage with the position of the temperature measurements in the water reservoir of the storage (approximately in the center) and in the ground closed to the storage (vertical measurements at the edge of the storage).

Figure 9: Picture of the pit heat storage before filling

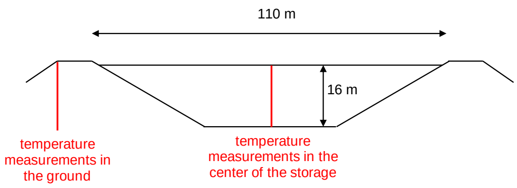

Figure 10: Cross section of the pit heat storage and position of the temperature measurements

In Figure 11 the water temperatures in the center of the pit heat storage measured in distances between 0 and 16m from the water surface on top are shown. Beginning with the relevant solar production in April of each year first the upper layers and about two months later also the lower layers started to raise the temperatures. The maximum temperature in the storage was reached in the beginning of September (the peak was about 82°C 4 m below the surface in 2014). Until the end of October the layers in the middle of the storage could keep the temperatures quite constant. The water temperature on top is dropping 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 a minimum between 20-35°C in all layers.

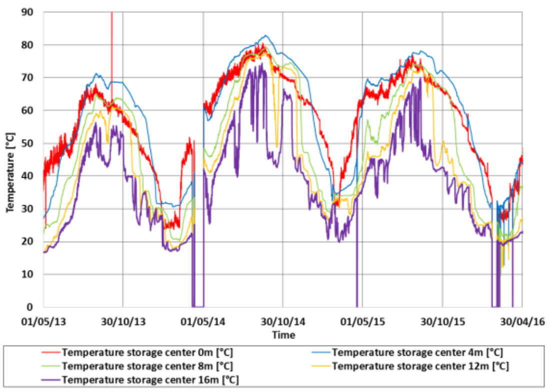

Figure 11: Trend of the water temperatures in the center of the pit heat storage during the 3 years monitoring period
Explanations: 0m ….. 16m: distances in meter below water level

Figure 12 shows the trend of the temperatures in the ground next to the storage in different depths below the surface (between 2 and 16m). While the temperature close to the surface (in 2 m depth) follows the seasonal temperature levels and amounts to 5 to 20°C all other temperatures had a steady increase starting at about 10°C in spring 2013 and ending at about 14-15°C at the end of April 2016. The reason for this is that the heat losses of the pit heat storage have already warmed up the ground around the storage. As a consequence the heat losses of the storage will be slightly reduced in the future due to the reduced temperature difference between water and soil. This aspect was expected in the design phase but could not be calculated in detail.

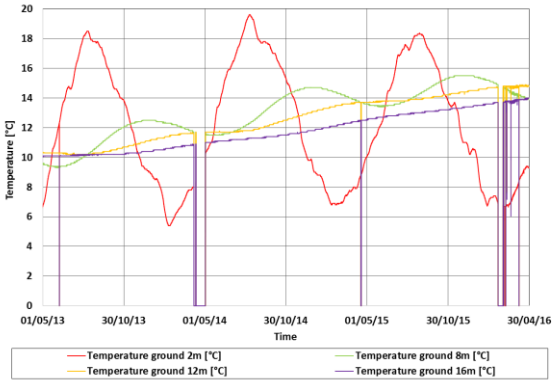

Figure 12: Trend of the ground temperatures next to the pit heat storage during the 3 years monitoring period
Explanations: 2m ….. 16m: distances in meter below ground surface

4.4 Overall operation of the new plant units

The trends of the thermal capacities of all heat generation units of the new plant is shown in Figure 13. The graphs for the heat pump and the biomass CHP plant have been already discussed in the chapters before while the characteristics of the heat production of the new solar plant and the charging and discharging of the pit heat storage and finally the resulting heat supply to the district heating grid is outlined here.

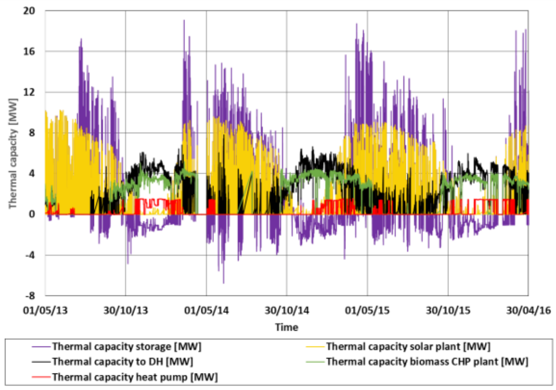

Figure 13: Trend of the thermal capacities of the overall plant during the 3 years monitoring period
Explanations: Thermal capacity storage: +…charging, -…discharging; not shown in this Figure is the heat production of the existing old solar plant and the corresponding additional heat supply to the district heating grid.

The solar plant reaches the maximum production in the period between April and June. The charging and discharging procedure of the pit heat storage is very dynamic in the summer period when no other heat producer then the solar plant is in operation. In the winter period between October and March there is practically no charging but only discharging of the storage.

In Figure 14 the same parameters are shown in cumulated values for the whole 3 years monitoring period. Charging and discharging of the pit heat storage are displayed in separate graphs in this figure. It can be pointed out clearly that in the winter period there is practically no charging, while discharging happens all over the year. Moreover, the biomass CHP plant contributes with the highest amount to the overall heat production.

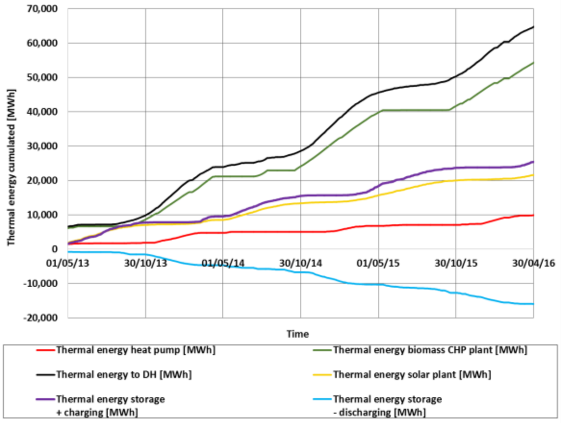

Figure 14: Trend of the cumulated thermal energy produced from the plant units during the 3 years monitoring period

Explanations: not shown in this Figure is the heat production of the existing old solar plant and the corresponding additional heat supply to the district heating grid

An overall balance for the new plant units during the monitoring period is shown in Table II (for year 1 from 01/05/2013 – 30/04/2014), Table III (for year 2 from 01/05/2014 – 30/04/2015) and Table IV (for year 3 from 01/05/2015 – 30/04/2016). The values for the heat losses of the storage, the change of heat capacity in the storage, the efficiencies and yields are calculated, all other parameters are measured. All numbers are related only to the new plant units without the existing system. The electric production of the biomass CHP is the gross electric production of the ORC, the electric consumption of the biomass boiler system and the overall hydronic system are not considered in these figures.

In year 1 60% of the total heat produced was generated by the biomass CHP system, 27% by the solar plant and 13% by the heat pump. The heat losses of the storage amounted to 2,685 MWh which is 11% of the total heat produced. At the end of this first monitoring year the thermal energy stored in the pit heat storage was 1,464 MWh higher than at the beginning of this period. The electric consumption of the heat pump amounts to about 45% of the electricity produced by the ORC, while the COP of the heat pump was 3.1 and the gross electric efficiency of the ORC was 18.9% in the first year. The yield of the new solar plant with 15,000 m² reached 448 kWh/m²,a which is about 10% higher than the project target of >400 kWh/m²,a. Considering that the old existing solar plant with 18,300 m² produces about 8,700 MWh/a of heat in average the total solar fraction of the overall plant (old and new) amounted to about 45%.

In year 2 the heat pump produced only two-thirds of the heat compared to the year before. This difference and the 25% increased heat demand were compensated by the biomass CHP plant. The COP of the heat pump (3.3) and the gross electric efficiency of the ORC (19.5%) were slightly higher. The reason for the increase of the COP of the heat pump was the higher average water temperature in the storage (due to higher annual solar energy production) feeding the heat pump evaporator. The increased electric efficiency of the ORC was due to the average operation more closely to the nominal load.

Year 3 of the monitoring period was similar to year one except that the solar production and therefore the solar yield was about 12% less due to unfavorable weather conditions. The heat capacity of the storage at the end of the period was about 1,000 MWh less than at the beginning.

Table II: Energy balances and key figures of the overall plant during the first year of the monitoring period

Unit		Heat production / utilisation 01/05/2013 - 30/04/2014	
		[MWh]	**[%]**
Solar sytem (15,000 m²)		6,724	*27%*
Heat pump		3,255	*13%*
Biomass CHP based on ORC		15,081	*60%*
Total heat production		**25,059**	***100%***
Heat from storage to heat pump	**-**	**2,202**	*-9%*
Heat losses of the storage	**-**	**2,685**	*-11%*
(-) increase or (+) decrease of thermal energy in the storage	**-**	**1,464**	*-6%*
Total heat supply to the district heating grid		**18,708**	***75%***
		Electric production (+) consumption (-) [kWh]	
Heat pump	**-**	**1,052,882**	
ORC		**2,343,860**	
		Efficiencies	
		COP [-]	**η-el gross [%]**
Heat pump		**3.09**	
ORC			**18.9**
		Yield [kWh/m²,a]	
Solar system (15,000 m²)		**448**	

Table III: Energy balances and key figures of the overall plant during the second year of the monitoring period

Unit		Heat production / utilisation 01/05/2014 - 30/04/2015	
		[MWh]	**[%]**
Solar sytem (15,000 m²)		7,160	*26%*
Heat pump		2,034	*7%*
Biomass CHP based on ORC		18,607	*67%*
Total heat production		**27,801**	***100%***
Heat from storage to heat pump	**-**	**1,412**	*-5%*
Heat losses of the storage	**-**	**2,946**	*-11%*
(-) increase or (+) decrease of thermal energy in the storage	**-**	**227**	*-1%*
Total heat supply to the district heating grid		**23,216**	***84%***
		Electric production (+) consumption (-) [kWh]	
Heat pump	**-**	**622,287**	
ORC		**3,003,680**	
		Efficiencies	
		COP [-]	**η-el gross [%]**
Heat pump		**3.27**	
ORC			**19.5**
		Yield [kWh/m²,a]	
Solar system (15,000 m²)		**477**	

Table IV: Energy balances and key figures of the overall plant during the third year of the monitoring period

Unit	Heat production / utilisation 01/05/2015 - 30/04/2016 [MWh]	[%]
Solar sytem (15,000 m²)	5,917	*25%*
Heat pump	3,126	*13%*
Biomass CHP based on ORC	14,587	*62%*
Total heat production	**23,630**	***100%***
Heat from storage to heat pump	**- 2,104**	*-9%*
Heat losses of the storage	**- 2,354**	*-10%*
(-) increase or (+) decrease of thermal energy in the storage	**973**	*4%*
Total heat supply to the district heating grid	**20,145**	***72%***
	Electric production (+) consumption (-) [kWh]	
Heat pump	**- 1,022,045**	
ORC	**2,552,898**	
	Efficiencies	
	COP [-]	**η-el gross [%]**
Heat pump	**3.06**	
ORC		**19.5**
	Yield [kWh/m²,a]	
Solar system (15,000 m²)	**394**	

3 SUMMARY AND CONCLUSIONS

Within the European demonstration project "SUNSTORE 4" an innovative, multi-applicable and cost efficient large-scale district heating system based on hybrid solar and biomass with a long-term pit heat storage and an Organic Rankine Cycle (ORC) for green electricity production was erected and put in operation mid of 2012. The plant is located in Marstal – Denmark and was an enlargement of the existing district heating facilities which consisted of several bio-oil boilers an 18,300 m² solar plant and 10,000 m³ pit heat storage.

The new plant consists of additional 15,000 m^2 solar system, a biomass CHP plant based on a thermal boiler, an ORC with 3.2 MW heat and 750 kW_{el} electric output and a flue gas condensation with 1.1 MW_{th}, a 75,000 m^3 pit heat storage and a 1.5 MW_{th} heat pump with CO_2 as refrigerant.

From May 2013 until April 2016 a continuous 3 years monitoring period of all new plant units has been performed. The results show that on average about 65% of the total heat produced was generated by the biomass CHP system, 25% by the solar plant and 10% by the heat pump. The heat losses of the new pit heat storage correspond to about 10% of the total heat produced.

The electricity production of the ORC is about 2-3 times higher than the electricity consumption of the heat pump and thus the plant is also a net green electricity producer. The average COP of the heat pump is 3.12 while the average gross electric efficiency of the ORC is 19.3%. The average yield of the new solar plant with 15,000 m² reached 440 kWh/m²,a. Under consideration of the old (existing) solar plant the total solar fraction of the overall plant (old and new) supplied to the district heating grid amounts to about 45%.

Moreover, within a one week test-run also the biomass furnace and boiler system was evaluated in detail. Using wood chips as fuel with an water content of about 27%, the results show a boiler efficiency between 87-88% (furnace incl. air pre-heater) while including the energy recovery of the flue gas condenser the efficiency raises to 103 to 104% (based on NCV of the fuel used).

The results of the monitoring period clearly show that the plant and the subsystems in general meet the targets of the nominal design parameters which have been a COP of the heat pump of 3.1, an ORC gross electric efficiency of 18%, a yield of the new solar plant of 440 kWh/m²,a and a biomass boiler efficiency including the flue gas condensation unit of 100%.

Furthermore, based on the monitoring results of the SUNSTORE 4 plant and its individual components a large potential for the dissemination of this technology exist all over Europe. Intensive acquisition activities for follow-up projects are ongoing especially in Scandinavia, Germany and Austria.

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10 LOGO SPACE

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