FIELD TEST FOR PERFORMANCE MONITORING OF COMBINED SOLAR THERMAL AND HEAT PUMP SYSTEMS

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1. Introduction

The technological combination of solar thermal systems with heat pumps continues to be a highly topical subject in the context of sustainable heating concepts, especially for single family houses. In the past years more and more different types of such combined systems have been developed and introduced to the market for both domestic hot water and space heating. The main background for this development is the expected increase of efficiency for both, the solar heating system and the heat pump, and further synergetic effects in comparison to separate conventional heating systems due to the mutual synergetic interaction of the components and high system integration. This can lead to high system performances, thus to a decrease of electric power consumption and emission of greenhouse gases like CO_2, respectively [Loose, 2010]. In addition, the reduction of the space heating load of new and renovated buildings leads to a relative increase of the fraction of energy required for hot water preparation. This effect is of significant importance for the combination of heat pump systems with solar thermal collectors since especially during the summer months a large share of the high temperature heat required for domestic hot water preparation can be produced by means of solar thermal. As result, higher seasonal performance factors (SPF) of the overall systems can be achieved.

The technical realisation of such a combination of different technologies has brought about a multitude of new system concepts on the market which have to be distinguished [Loose 2011a]. However, up to now uniform and objective criteria for the evaluation of the solar and heat pump systems' thermal performance are not yet available. For this purpose, new testing procedures for this kind of systems are being developed at ITW and other institutions. These procedures are based on performance tests in the laboratory and in situ, as well as corresponding simulations and the definition of system performance factors. Activities in this field are concentrated in the IEA SH&C Task 44 / IEA HPP Annex 38[1] named "Solar and Heat Pump Systems" [Hadorn 2010] in which the ITW currently participates. This paper presents results of completed and running field tests of different concepts of combined solar and heat pump systems with different heat sources.

2. Performance test of solar heat pump systems and field tests

Many manufacturers of combined solar and heat pump systems advertise their products by declaring relatively high system performance factors, especially for such types of systems in which solar thermal unit and heat pump are connected in a serial way, i.e. in which the heat pump can be provided with a higher source temperature while the solar collector might be operated at lower return temperatures, respectively. Up to now, these performance factors cannot be validated by laboratory tests for most types of systems and they also cannot be verified by the customer because neither objective performance test methods nor quality labels (like the *solar keymark* for solar thermal collectors and systems) are available for these combined systems.

Results from field tests with solar combisystems have shown that the effective thermal performance of the heating systems in real operation depends significantly on the quality of installation and cannot be derived directly from the sum of performance factors of the single components measured in the laboratory [Ullmann 2010, Mette 2011, Loose 2011b]. Therefore, not only the performance of the solar thermal collector and the heat pump as such is important, but also the quality of the thermal insulation or the thermal stratification of the heat store. For combined systems, also hydraulics and controlling are of significant importance and the more complex a combined solar and heat pump system is built up the more important becomes the careful attention to a reasonable sequence of the different possible modes of operation. Nonetheless, the real behaviour of these systems can only be determined by means of in situ monitoring over a longer time period (at least one year).

[1] IEA: International Energy Agency, SH&C: Solar Heating and Cooling Programme, HPP: Heat Pump Programme

While for conventional – not combined – solar and heat pump installations broad studies and field tests have already been conducted in order to determine the thermal performance under real operating conditions [Miara 2011, Combisol 2010], for the combined solar thermal and heat pump systems only relatively few experiences from single installations are known until now.

In order to be able to describe the energetic performance and the environmental impact of combined systems using solar thermal and heat pumps in an objective manner, corresponding test and assessment procedures are necessary. These methods are not yet common standard. In this context, performance test methods are being developed at ITW for laboratory measurements [Mette 2009]. Here, the main focus lies on a method which is adapted from the CTSS test method (Component Testing – System Simulation) and uses a component orientated approach which is based on physical tests of the key components. The aim of the component tests is the determination of all relevant component parameters for the detailed description of the thermal behaviour of the individual components. Therefore, numerical models are required in order to describe the dynamic behaviour of the specific components. Parameters of these models are determined by means of parameter identification using measured data from several test sequences of the component testing. Based on the parameters determined for the different components, the annual thermal performance of the complete system can be predicted for defined reference conditions (meteorological data, load profiles) by using a component based simulation program such as TRNSYS [Mette 2009, Frey 2010]. The further development of a novel test method for the thermal behaviour of heat pumps under dynamic conditions is part of the new project *WPSol* ("Performance testing and ecological assessment of combined solar thermal and heat pump systems"). Within this project measurements of different heat pumps are performed at the new heat pump test facility of ITW. Furthermore numerical simulation models are developed for the detailed description of the heat pump's dynamic thermal behaviour combined with the entire solar heating system. A subsequent validation of this assessment procedure on the basis of *in-situ* measurements of seven combined solar and heat pump systems of different types installed in single-family houses is planned, as well. In parallel, simulations with the software TRNSYS are performed to predict the thermal behaviour of the heating systems for a period of one year. The first combined solar and heat pump systems have been installed in single-family houses in Germany and monitoring equipment was mounted during the first months of 2011. Three out of seven systems are solar thermal systems combined with air to water split heat pumps provided by Schüco International KG. This company has gained field test experience during the past years and a new seasonal performance factor including solar yield has been proposed for such type of heating systems by an employee of Schüco [Thole 2010]. Also ITW has performed many field tests, e.g. within the European project *CombiSol* [combisol project 2010]. This paper will present field test results of different combined solar and heat pump systems in single-family houses in Germany. Two different heating systems will be described, the first of which has been monitored over a period of three years, while the monitoring of the second system has started in 2011. Both installations can be differentiated by the heat source of the heat pump (brine/water vs. air/water heat pump) and by their different applications in new buildings and older housing stocks, respectively.

3. Performance figures for combined solar thermal and heat pump systems

The boundary conditions to be used for the energetic balance of combined solar thermal and heat pump systems still have to be defined. Depending on these conditions the system monitoring has to be performed on a more or less detailed level. Since no generally accepted performance factors for combined solar thermal and heat pump systems exist by now, such performance figures have been proposed at the 3rd IEA Task44 /Annex 38 meeting earlier this year (c.f. fig. 1). Several different figures can be taken into account, starting with the heat pump only (e.g. COP – coefficient of performance) or the solar part only and including more and more parts of the system, e.g. hot and cold storages, back-up heating and the heat distribution system, until all heat flows and final energy consumptions are taken into account. This latter figure is called system or solar seasonal performance factor (SPF6) and covers the overall system. At present, the performance factors are numbered SPF1 to SPF6, which might be changed into more plausible terms or abbreviations later. In order to be able to calculate the system SPF from measured data, at least the complete used energy for space heating and domestic hot water preparation has to be measured, as well as the final energy consumption (electric energy in this case). For all SPF's with lower characteristic number additional sensors have to be used for monitoring in order to determine specific heat flows and energy consumptions. The exact definition of the calculated performance factor has to be given in any case, in order to make these values comparable to other systems. If additional simulations of the system will be carried out which need to be validated by measured data, a more accurate (i.e. more detailed) monitoring needs to be performed. Additional factors like the primary energy ratio (PER), solar fractions or CO_2-emissions can be calculated furthermore [Malenković 2011].

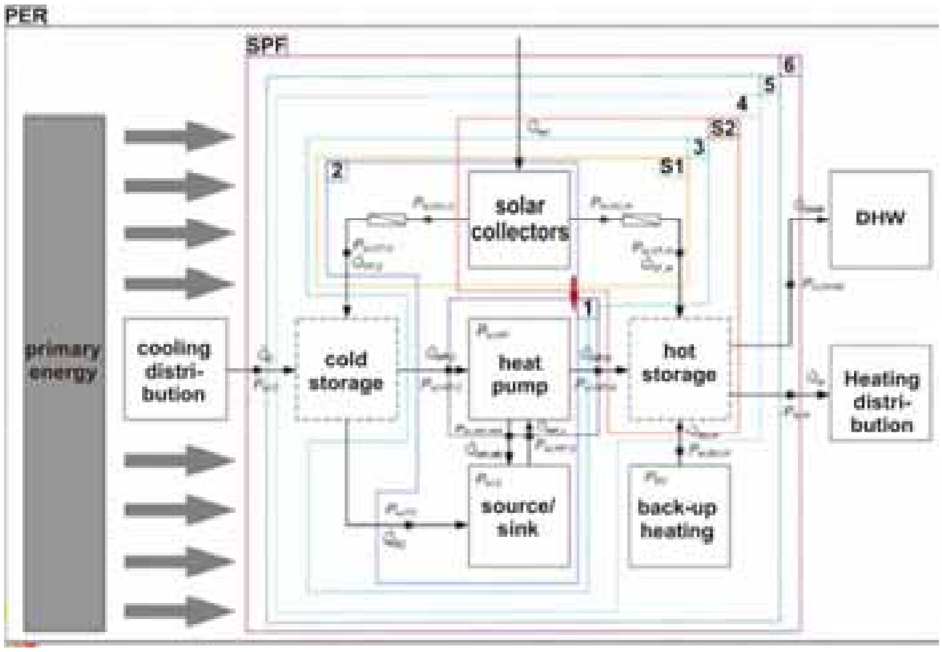

Fig. 1: Proposal for the definition of performance figures for combined solar and heat pump systems [Malenković 2011]

4. System using a ground source heat pump with borehole heat exchanger and solar collector (System A)

4.1 System description

The first monitored system is meant for the use in new buildings with lower thermal heat demand and low temperatures in the heating circuit, e.g. due to floor heating. In combination with an additional photovoltaic installation, even a net zero energy house can be achieved based on an annual energy balance (c.f. fig.2). The system consists of the following components:

- Brine/water heat pump: low temperature heat pump with 5 kW output, COP at B0/W35 = 4.2[2]
- Borehole heat exchanger, length 75 m
- Solar thermal installation: system for solar domestic hot water preparation and space heating with approx. 11 m² collector surface and 750 l solar combi storage; low-temperature collector designed especially for this application (resistant against inside condensation of atmospheric humidity).
- Photovoltaic installation: installed output approx. 2.2 kWp (not monitored).

Fig. 2: Schematic view of the monitored system A, 1: solar thermal collectors, 2: solar hot water storage and solar station, 3: brine/water heat pump, 4: borehole heat exchanger, 5: PV modules, 6: power inverter, 7: electric meter [Schüco]

[2] COP = coefficient of performance at the operating point B0/W35, i.e. heat source temperature 0°C (brine) and heat sink temperature 35°C (water), determined according to the European standard EN 14511

The house is a single family house located at Herford near Bielefeld, year of construction 2006, with 140 m^2 heated living area, 47.5 kWh/(m^2a) space heating demand, 5.8 kW required heating load, 4 persons in the household, floor heating 35/28°C. According to VDI 4650, 2006 the seasonal performance factor (SPF) calculated for space heating only is SPF = 4.1 [Thole 2010a-d].

In addition to the traditional direct utilization of the solar energy delivered by the collectors for domestic hot water preparation and space heating, solar gains which are insufficient for direct use or surpluses, e.g. when the hot water storage tank is fully charged, can be used to support the heat pump and to actively regenerate the ground via the borehole heat exchanger. The following four modes of operation are possible (c.f. fig. 3):

1) Direct use of solar energy with sufficient temperatures by charging the combistore for domestic hot water preparation and space heating.
2) Solar support of the heat pump by raising the temperature level in the primary (brine) circuit.
3) Solar thermal regeneration of the borehole heat exchanger while the heat pump is switched off and solar yield is available (with collector temperatures below 12°C).
4) Use of the solar heat stored in the ground during the first months the heat pump is operated again after the summer months.

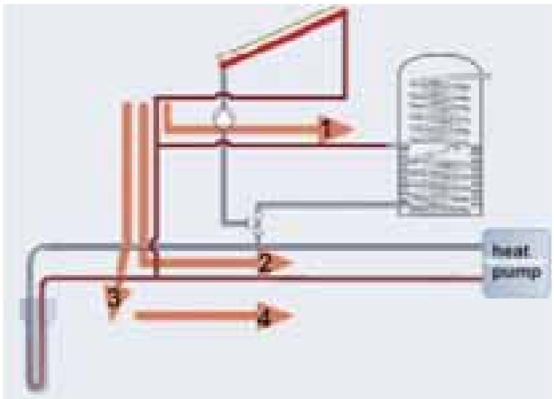

Fig. 3: Possible modes of operation in the monitored system A

The so called active regeneration of the ground means direct warming of the soil with solar yields. While this operating condition is in use, brine with temperatures between 6 and 12°C is led into the solar collectors. Because of these low temperatures the ground can be thermally regenerated by using solar energy even during days with low solar irradiation. Direct charging of the hot water storage can be performed with collector temperatures between 25 and 110°C and requires solar irradiation of more than 250 W/m^2. The solar energy used for regeneration is additional solar gain which would not be used at all in traditional solar thermal systems, yet it increases the efficiency of the heat pump (increase of COP approximately by 2.5 % when the heat source temperature is increased by 1 K). However, the additional electric energy consumption of the circulation pumps must be accounted for in the energy balance, too [Thole 2010].

After a long heating period temperatures of less than -5°C can be reached in the borehole heat exchangers. When the active regeneration of the ground is in operation, brine temperatures can thus be lower than the ambient temperature. This effect leads to condensation of air humidity within the solar collector. Due to this a special collector design is required for this type of application (special thermal insulation and drainage holes). With the possibility of using additional solar gains at low irradiation and low temperatures, the specific collector yield can be increased by ca. 10 % and solar yields of 600 kWh/(m^2a) and more can be reached [Thole 2010b, d].

4.2. Monitoring results

In order to verify the results achieved from simulation studies for the optimal control strategy, the solar and heat pump combination type A was monitored within a field test of selected pilot installations over a period of three years (2007/2008 – 2009/2010). For the acquisition of the different energy quantities which are the basis of latter energy balances, the systems were provided with measurement equipment already at the time of the installation. Furthermore, sensors for the following data have been installed:

- Solar irradiation
- Ambient temperature
- Temperatures in the ground
- Temperatures of the heat source (the temperature of the fluid in the borehole heat exchanger)
- Electrical power consumption of the compressor
- Operation times of the pumps.

As result over three heating periods the following facts can be seen:
A cooling down of the borehole heat exchanger over the years could be avoided. The temperatures in the ground near the borehole heat exchanger were not below 1°C at any time. After one year the temperature of the heat exchanger reaches the same value as at the start of the monitoring procedure (c.f. fig. 4 and 5) [Thole 2010a].

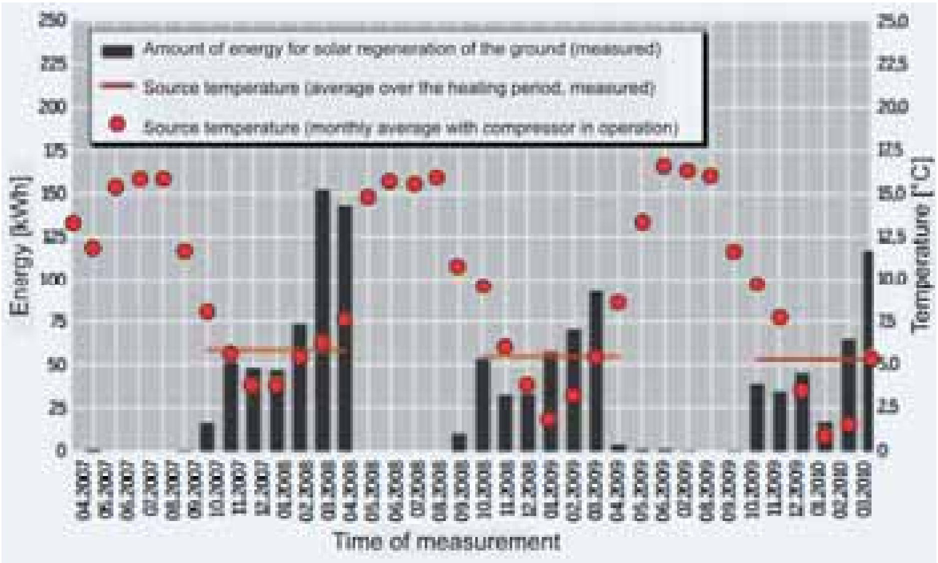

Fig. 4: Time dependent course of the borehole heat exchanger temperatures and solar regeneration of the ground

The ground cannot be seen as a seasonal storage, because a one borehole system for a single family house is too small and thermal losses are too high. However, solar regeneration up to the undisturbed original temperature state is possible, which results in higher heat source temperatures for the heat pump than in conventional ground source heat pump systems without solar regeneration. In addition, no further temperature decrease occurs during operation in the following years. The course of the temperature of the borehole heat exchanger confirms the solar regeneration of the ground during periods of low solar irradiation, also in winter and spring, as can be seen from the amount of energy used for solar regeneration of the ground shown by the dark bars in fig. 4. The temperature of the solar collector for regeneration in summer was limited to 12°C, dependent on the temperature of the undisturbed earth and for an optimized electrical power consumption of the pumps [Thole 2010b].

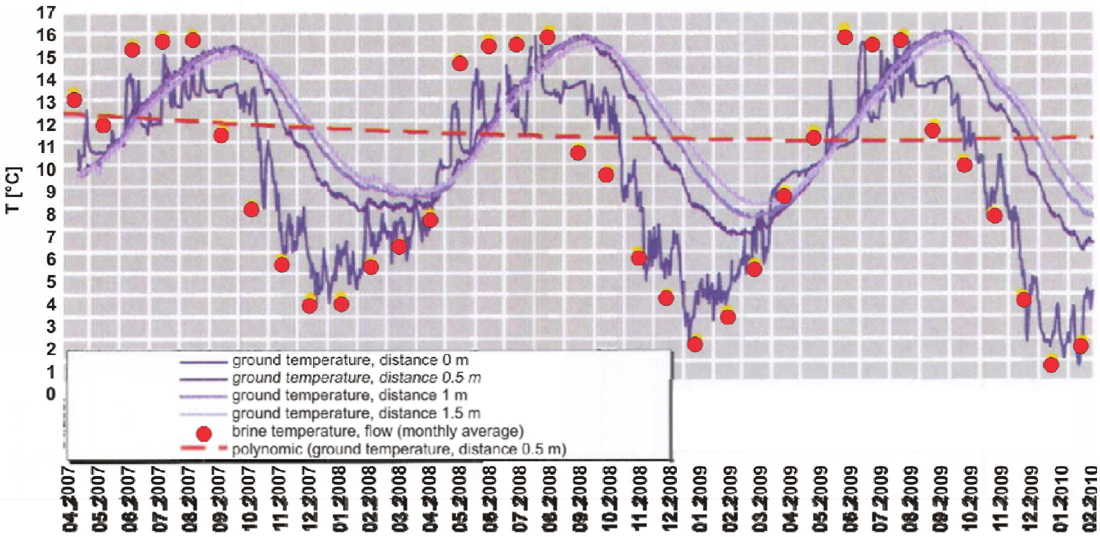

Fig. 5: Time dependent course of the source and ground temperatures over three heating periods

The seasonal performance factor (SPF) of the heat pump corresponds to the calculation according to the German standard VDI 4650 with an assumed mean heat source temperature of 5°C due to the solar regeneration of the ground. (The normal base for calculations is 2°C for borehole heat exchangers and 0°C for horizontal heat exchangers instead of 5°C). The SPF is calculated from the ratio of useful energy output Q_{HP} of the heat pump to the electrical energy input W_{el}, integrated over an entire heating period:

$$SPF_{HP} = Q_{HP} / W_{el} \qquad \text{(eq. 1)}$$

The seasonal performance factor for the combined system was calculated as ratio of the energy gains of heat pump and solar thermal system and the electric energy required for the operation of the heat pump and the solar thermal system [Thole 2010b]. The SPF for the complete system could be increased by an average of 35 % as result of the solar gains and verifies the simulated predictions. The SPF of the 5 kW heat pump installed in the new built low energy house amounts to 4.1 according to simulations without solar coupling for space heating only. The solar and heat pump combination reaches an SPF of more than 5, both from simulation and measured data (c.f. fig. 6). This is due to

- higher average temperature of the brine in the primary circuit of the heat pump
- lower operating time of the heat pump, and
- direct use of solar energy in bivalent regenerative operation[3], thus decreased electrical power consumption of the heat pump (-25 %).

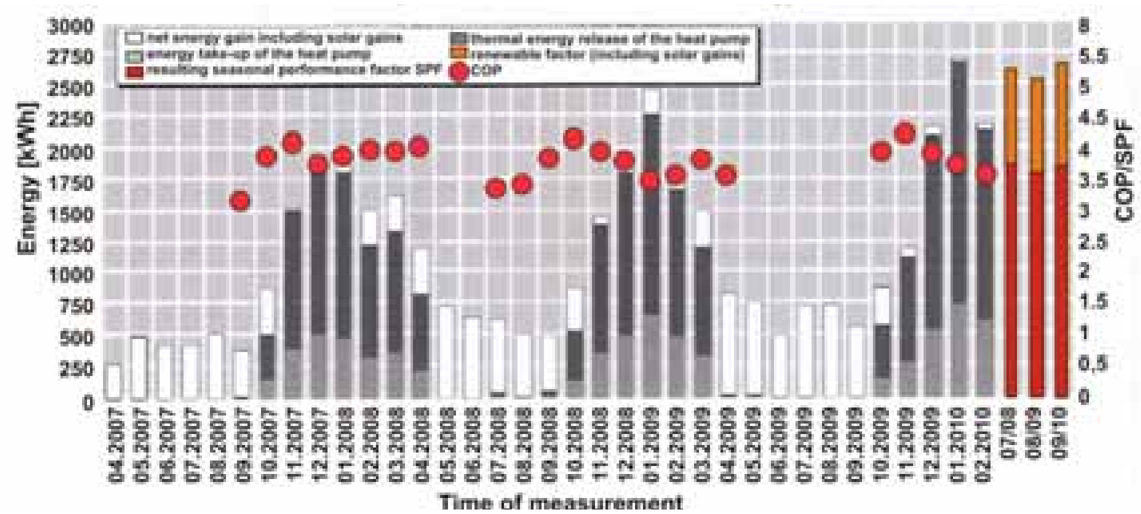

Fig. 6: COP and system SPF as well as energy quantities during a 3 year period

The performance factors shown in fig. 6 have been determined from the field test measurements as follows:

1) COP = seasonal performance factor of the heat pump: measurement of heat supplied by the heat pump and electrical power consumption of the heat pump including the primary pump.
2) Renewable factor = additional gains by the solar thermal system: measurement of the net solar yield plus heat losses of the store of a reference heat pump domestic hot water storage (e.g. 1.7 kWh/d for a 300 l store).
3) System SPF including solar gains = environmental heat (ground and solar) + electrical power consumption (compressor + brine pump + solar pump)/electrical power consumption. The system SPF is the sum of the averaged COP values (heat pump SPF) over one year + renewable factor in fig. 6 at the right side).

The determined average SPF for the heat pump only (without solar contribution and combined with floor heating systems) of 3.7 (see fig. 6) lies above the values known from field tests with heat pumps only in Germany. E. g. a survey of the Lokale Agenda Lahr results in a value of 3.4 for ground source heat pumps with floor heating systems [Lokale Agenda 2006]. A Swiss study gives as mean value of about 100 installed brine/water heat pumps an SPF of 3.5 [Erb 2004].

[3] Bivalent operation of a heat pump in general means an additional fossil back up for the heat pump for very low temperatures. In this case the heat pump is supported by the gas boiler and the solar thermal system stands for the additional renewable, i.e. regenerative part.

5. Hybrid system using an air to water split heat pump, solar thermal and gas boiler (System B)

5.1 *System description*

The second solar and heat pump system is being monitored starting in 2011 as part of the ITW project *WPSol* in cooperation with Schüco International KG in this case. The heating system is called by the manufacturer "hybrid heat pump – a multi-heat system for energy-efficient modernisation". The hybrid heat pump system was especially developed for the retrofitting of old central heating systems without the need for a building renovation at the same point. Hence the major change in the building's heating system is to replace the old boiler by the hybrid heat pump system. The integration of solar thermal, air/water heat pump and gas condensing boiler means considerable savings without intervention in the building and the heating system. In particular, high flow temperatures of up to 70°C for the space heating system are no problem in combination with a gas condensing boiler. By restricting to a bivalent alternative mode of operation (i.e. the heat pump and the gas boiler don't work at the same time), the contribution of the heat pump may be relatively small, in spite of the high heating load of the building. In this way, the hybrid heat pump represents an energy-efficient and economical alternative to high temperature heat pumps. According to the manufacturer, the gas consumption for this combination can be reduced by over 80 % when upgrading from an old atmospheric gas boiler to a hybrid heat pump system installation [Thole 2010a]. The monitored system consists of the following components (c.f. fig. 7):

- Air/water split heat pump: low temperature heat pump with 14 kW output, COP[4] at A2/W35 = 2.7, Zubadan technology (by means of a flash injection circuit in the external evaporator unit of the split heat pump air temperatures as low as -15°C can still be used as "heat" source).
- Solar thermal installation: system for solar domestic hot water preparation and space heating with approx. 10 m^2 collector surface and 750 l solar combistore; double glazed collectors.
- Condensing gas boiler, 25 kW.
- Photovoltaic installation: installed output approx. 2.1 kWp (not monitored).

The house is a single family house located at Lotte near Osnabrück, year of construction 1980, retrofit in 2010, with 190 m^2 heated living area and 4 persons in the household (two adults/two babies), floor heating 35/28°C.

Fig. 7: Schematic view of the monitored system B, 1: solar thermal collectors, 2: hybrid heat pump, 3: external split unit

The hybrid heat pump system consists of well known components which are combined in a new way, thus three different aspects are combined: A solar thermal system covers the domestic hot water load during the summer and assists the condensing gas boiler during winter time. An air/water split heat pump covers the heating load efficiently only during periods with relatively high ambient temperatures and still low system temperatures in the radiators. The condensing gas boiler covers the high heating load during the few real cold winter days

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[4] COP = coefficient of performance at the operating point A2/W35, i.e. heat source temperature 2°C (air) and heat sink temperature 35°C (water), determined according to the European standard EN 14511

effectively, when high system temperatures are required. The so called bivalent point, at which the gas boiler takes over and the heat pump is switched off, lies around 0°C ambient temperature (c.f. fig. 8).

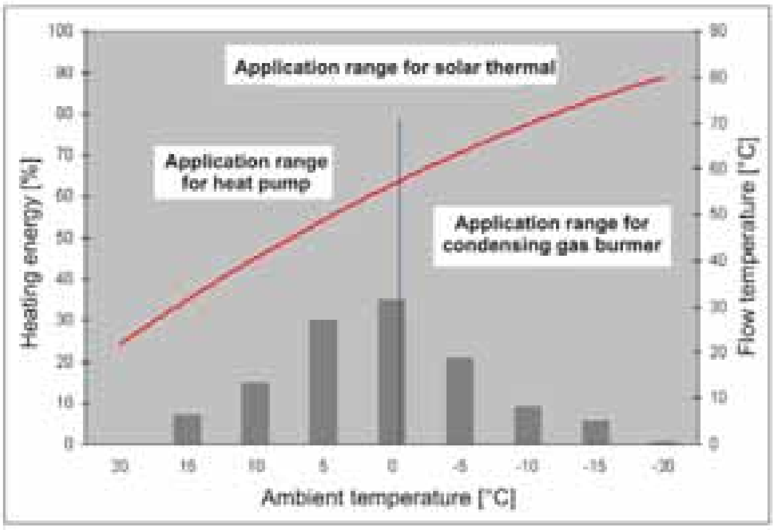

Fig. 8: Definition of the application ranges for the hybrid heat pump system depending on ambient and flow temperatures

The hybrid heat pump system can be operated in the following modes:

- Charging the combistore with solar thermal
- Charging the combistore with the heat pump or gas boiler
- Space heating via heat pump or gas burner directly
- Solar space heating from the combistore
- Combinations of the above mentioned modes
- Domestic hot water preparation by the combistore
- Defrosting the evaporator of the air/water heat pump with energy from the combistore, i.e. without fossil energy like electricity.

The different modes of operation listed above have to be distinguished over a period of time and be taken into account for the monitoring procedure.

5.2. Monitoring

The monitoring equipment applied within the project *WPSol* is based on the one used within the European project *CombiSol* [Mette 2011, Ullmann 2010, Combisol 2010] for field tests of solar combisystems for domestic hot water preparation and space heating. In our case, the equipment was extended with emphasis on the additional requirements related to the heat pump, especially by the use of more than one electricity meter and a sensor for air humidity. The following sensors are applied (c.f. fig. 9):

- Temperature sensors Pt 1000 for ambient temperature (outside), room temperature in the cellar, thermal stratification in the combistore, temperatures in the primary circuit of the heat pump
- Temperature of the heated living area
- Solar irradiation
- Air humidity outside
- Heat meters (ultrasonic flow meters and 2 x Pt 500 temperature sensors each) for solar circuit, domestic hot water circuit, hot water circulation, storage charging circuit, two heating circuits (floor heating), “bivalent renewable circuit” (for solar heating from the combistore and defrosting of the evaporator of the air/water heat pump), gas boiler circuit and the heat pump circuit
- Electric energy meters for the electricity consumed by the compressor of the heat pump, controller, pumps and other parasitic electricity.

Data are measured every second and values for every minute are transferred once per day via mobile communication to ITW.

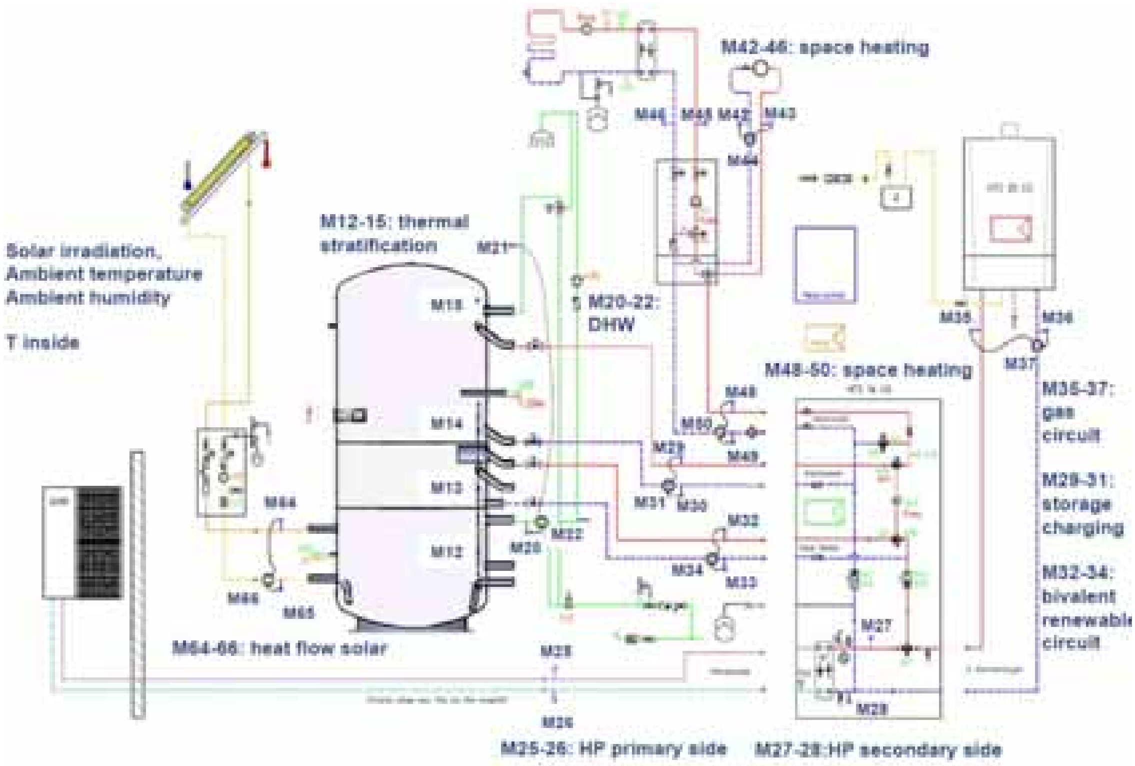

Fig. 9: Monitoring concept for the hybrid heat pump, system B

Since the in situ measurements within the ITW project *WPSol* have just started in 2011, not enough data for feasible energy balances are available yet; especially no data from heating periods in winter. Instead of this, some exemplary first monitoring results are shown in fig. 10 for one day in July, 2011.

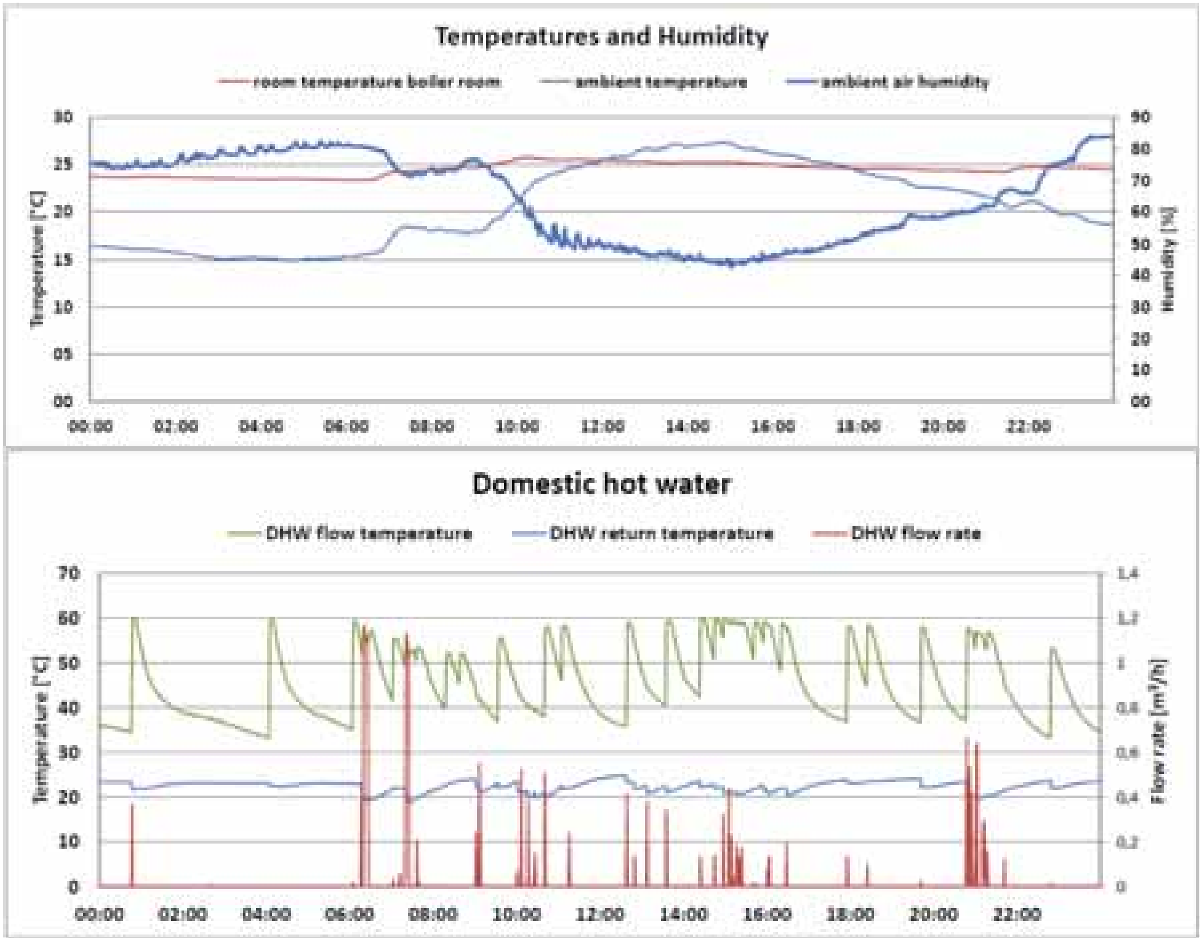

Fig. 10a: Exemplary results for the hybrid heat pump for July 12th, 2011

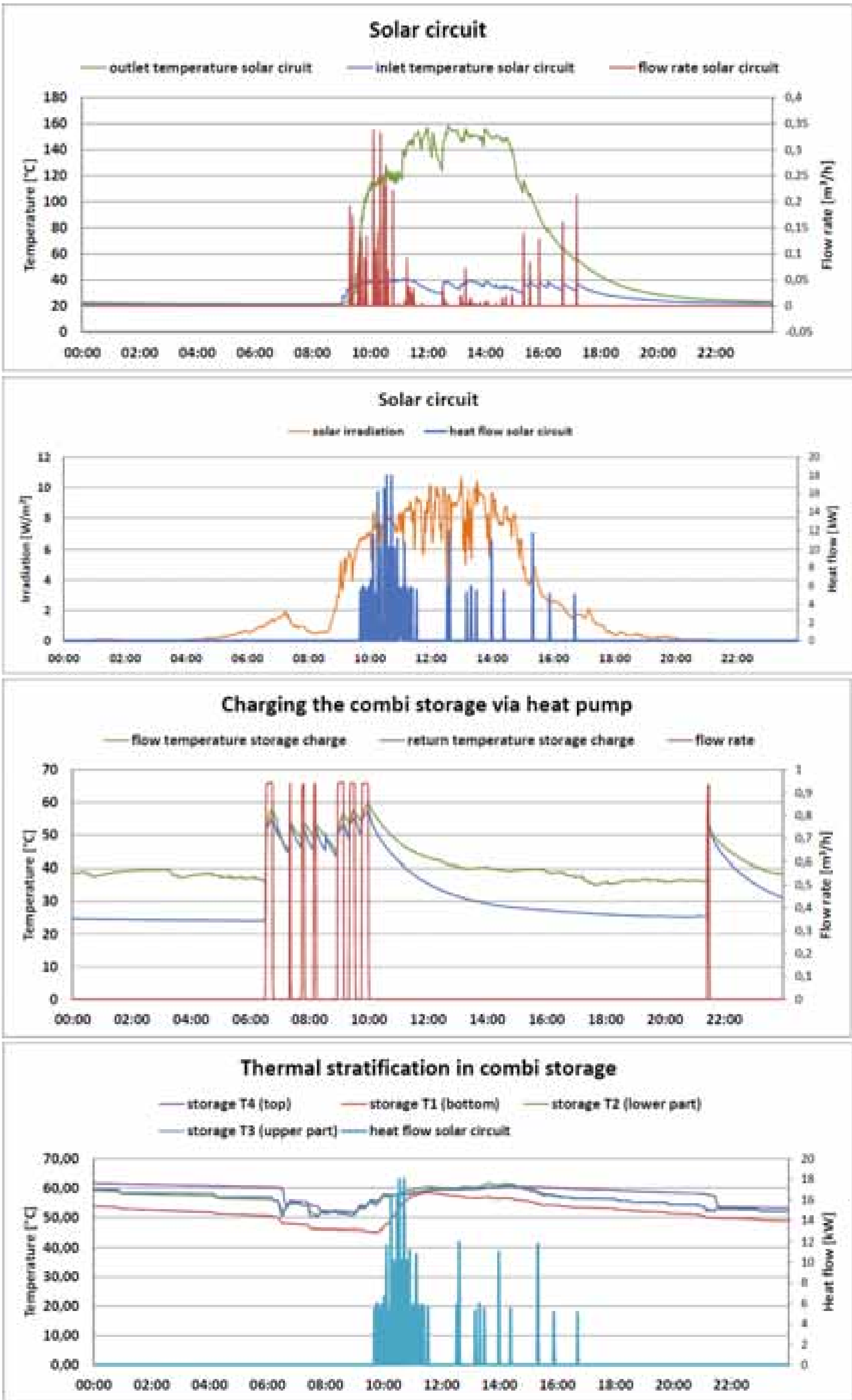

Fig. 10b: Exemplary results for the hybrid heat pump for July 12th, 2011

It is too early for energy balances, but one can see in the diagrams shown above that reasonable data are being measured. The ambient temperature and humidity are important for the behaviour of the air to water split heat pump with the evaporator being located outside the building. When the ambient temperature rises, air humidity decreases. The domestic hot water circuit and the solar circuit show reasonable values for flow and return temperatures, which fit the corresponding tapping profile and the solar irradiation, respectively. All the other monitored heat flows are similarly reasonable. The combi storage of the hybrid system might be charged by the solar collector or by the heat pump/gas unit. The reactions of the combi storage to the different charging processes can be seen, as well. In conclusion, the monitoring system is running in a stable way by now. However, measurements need to be followed over a longer period of time before a serious assessment of the heating system will be possible.

6. Summary and conclusion

Field tests of solar thermal and heat pump systems have shown that the thermal behaviour and performance of the systems under real operating conditions depend on the control strategy and the interaction between the individual components. This is especially true for combined solar and heat pump systems which have available many distinguished modes of operation.

As for this type of systems for domestic hot water preparation and space heating only few field test data from single installations are known, monitoring is being strengthened within the IEA SH&C Task 44 / HPP Annex 38 “Solar and Heat Pump Systems” in order to have a better basis for the assessment and comparison of the systems’ performances.

Two solar and heat pump systems have been presented. The first one disposes of a borehole heat exchanger while the second system includes an air to water split heat pump and an additional gas boiler. Both systems can also be differentiated by their target buildings: newly built single family houses in the first case and retrofitting of older buildings in the second case. The first installation has been monitored over a period of three years and showed good results. The solar regeneration of the geothermal probes ensures a high temperature level in the ground, so that the heat pump can be operated with a high system performance factor (SPF) in the long term. Result of the field test is an impressive confirmation of the high solar SPF of over 5 for the combined system, and of the stable ground source temperatures during several operating periods.

The second system called hybrid solar and heat pump system due to the additional condensing gas boiler is one of seven systems to be monitored within the ITW project WPSol. Measuring equipment has been installed in the beginning of 2011 and measurements are ongoing. Reliable data are expected for 2012.

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