Hardware-in-the-Loop Tests on Complete Systems with Heat Pumps and PV for the Supply of Heat and Electricity

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Abstract

Four “smart control” heat pump (HP) heating systems have been tested and evaluated as a whole by detailed measurements in the laboratory with a hardware in the loop approach. The complete systems were installed on a test rig that emulated a building with photovoltaic (PV) electricity production as well as the heat demand for domestic hot water and space heating and the electricity demand for household appliances. The test bench also emulated the environmental heat (air or ground source) as the source of the heat pump. The measurement focused on the capability of the tested systems to deal with solar power in excess to household needs and with different types of energy storage (thermal or electrochemical). In addition to insights into the behavior and performance of the tested systems, insights into the advantages and disadvantages of various key performance factors for these kind of systems were gained. It is found that self-sufficiency and self-consumption are not suitable optimization parameters. The grid purchase ratio is proposed instead.

Keywords: PV, heat pump, hardware in the loop, thermal energy storage, battery, self-consumption, self-sufficiency, control strategies, grid purchase ratio

1. Introduction

Single-family houses are no longer just energy consumers, but also energy producers. The combination of heat pump and PV systems reflects this very well. Corresponding products are already on the market: Heat pump systems whose control is designed for an increased self-consumption.

This work shows test results of four systems that aim to increase self-sufficiency and decrease electricity costs for households.

2. Methods

The Concise Cycle Test (CCT) is a test method for testing complete heating systems under realistic conditions. Originally developed to test systems with thermal collectors in combination with oil, gas and pellet boilers (Haberl et al. 2009; Haller et al. 2013), the method and the associated test infrastructure have meanwhile been expanded. This means that heat pumps and PV systems can now also be tested using the hardware-in-the-loop method (Haberl et al. 2014). The test method has thus developed from a test method for heating systems that provide space heat and domestic hot water to a test method for systems that supply heat and electricity for buildings. A description of the test method (in German) can be found in Haberl et al. 2018.

On the test bench the realistic operation of a complete heating system in the hardware-in-the-loop method is being enabled. During the test cycle, the test bench simulates and emulates a complete building whose heat and power requirements must be covered. This emulation also includes the building envelope with a photovoltaic system, the environmental heat as a source of a heat pump (ambient air or geothermal borehole probes) and the electric energy demand of home appliances (household electricity). The applied loads for space heating, hot water and household electricity are pre-defined to ensure an identical load and thus allow a direct comparison of the tested systems.

The procedure for simulation and emulation can be described as follows: The test bench software transfers current measured values to the simulation software at the end of each time step. In the simulation, the behavior of the respective component is calculated according to the input data and communicated to the test bench software.

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During each time step, the test bench software controls the emulation while the simulation software pauses. Only at the end of the time step are the new measurement data transferred to the simulation software, and the control target variables for the next time step are determined by the simulation software.

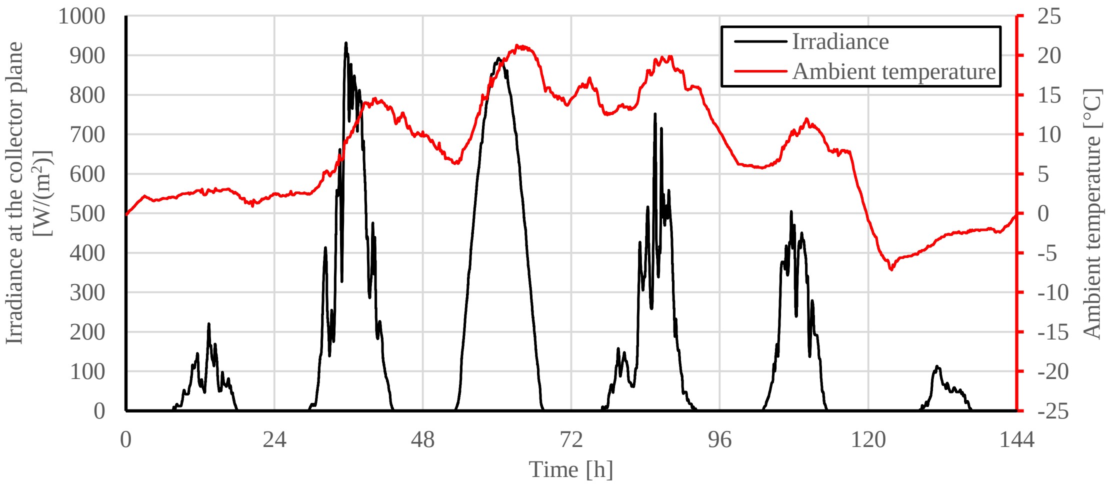

Figure 1: Weather data of the 6-day test cycle for the CCT.

Figure 1 shows the weather data of the 6-day test cycle of the CCT, which are representative to a whole year (Battaglia et al. 2017). Further boundary conditions of the test method are:

- PV system: 2 x 12 modules, 5.76 kWp, orientation south, tilt angle 45° (Max Power: 240 W; Open circuit voltage: 52.4 V; Short Circuit Current: 5.85 A)
- Space heating: Heating floor 140 m^2, 7.4 MWh/a respectively 120 kWh in a 6-day test
- Domestic hot water: 4 persons, 3 MWh/a respectively 50 kWh in a 6-day test, max. flow rate 18 l/min
- Household appliances: 4 persons, 3.3 MWh/a respectively 55 kWh in a 6-day test; Profile resolution 1 min.; max. power 5 kW

Both, thermal and electrical power, are measured in the system test. The thermal output is measured at the interface to the test bench via immersed temperature sensors in the flow and return lines and a volumetric flow meter.

The electrical power is measured at several positions during the test. The important variables for the energy balance are measured galvanically integrated. These are:

$E_{PV-yield}$ Produced PV electricity. The measurement is carried out on the DC and AC lines; the AC current measurement is used for the energy balance.

E_{HH}: Household electricity (without heat pump).

$E_{grid-purchase}$ Electric energy from the grid.

$E_{grid-feed-in}$ Electric energy supplied to the grid.

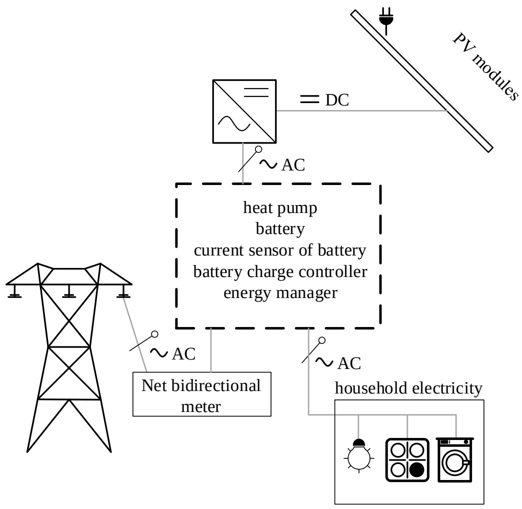

Figure 2: Fixed (galvanically integrated) measuring points. In addition, non-contact measurements are carried out within the tested system.

Various key figures are determined from the measurement data of the system test. The self-consumption ratio ($R_{self-con}$) indicates the share of locally produced PV that is being used on-site (eq. 1). The level of independence from the external power grid is described by the degree of self-sufficiency (R_{suff}, eq. 2). The PV generation ratio

(R_{gen}, eq. 3) describes the ratio of PV yield to total electrical energy consumption. A system with $R_{gen} = 1$ corresponds to a net-zero energy building. Due to the different efficiencies of the different systems tested and thus different values for the total energy consumption ($E_{consumption}$), the PV generation ratio can vary despite the same size of PV system and the same useful energy demand in terms of heat for space heating and DHW and electricity for the household. The grid purchase ratio (R_{net}, eq. 4) describes the ratio of energy purchased from the grid to total useful energy demand (E_{use}) for household electricity, domestic hot water (Q_{DHW}) and space heating (Q_{SH}, eq. 5). In this way, a mixed calculation of thermal and electrical energy is used. The advantage, however, is that all variables are defined by the test method and are identical for all tests.

$$R_{self-con} = \frac{E_{consumption} - E_{grid-purchase}}{E_{PV-yield}} \qquad \text{eq. 1}$$

$$R_{suff} = \frac{E_{consumption} - E_{grid-purchase}}{E_{consumption}} \qquad \text{eq. 2}$$

$$R_{gen} = \frac{E_{PV-yield}}{E_{consumption}} \qquad \text{eq. 3}$$

$$R_{net} = \frac{E_{grid-purchase}}{E_{use}} \qquad \text{eq. 4}$$

$$E_{use} = E_{HH} + Q_{SH} + Q_{DHW} \qquad \text{eq. 5}$$

3. Tested Systems

Four different systems were installed and tested on the test bench. The installation includes all hydraulic components as well as a complete electrical installation to supply the building with electricity. The tested systems had to work autonomously to meet the building's heat and electricity requirements. This also includes determining the current surplus of PV electricity and a strategy to utilize this energy.

The common feature of all tested systems is a 5.8 kWp PV system and a heat pump. The PV system size has been chosen such that its annual electricity yield corresponds roughly to the annual electricity consumption for the heat pump heating system and the household appliances. Thus, a net-zero energy balance may be achieved.

The concepts of the different tested systems differ considerably. Table 1 gives an overview about the storage concepts and the type of heat pumps of the tested systems.

Table 1: Storage capacities of the tested systems (thermal and electric) and source of the heat pump.

Tested systems:	**2TankBrine**	**CombiBatAir**	**CombiAir**	**CombiBatBrine**
Thermal Energy Store	DHW storage tank + heating buffer	Combistore	Combistore	Combistore
Volume	500 l + 300 l	600 l	900 l	900 l
Electrical Storage Device	No	Yes	No	Yes
Useable capacity	-	6.5 kWh	-	6.9 kWh
Source of the heat pump	Brine	Air	Air	Brine

4. Results

The systems that were tested in this project aimed to increase self-sufficiency and decrease electricity costs for the household. This was done by a smart handling of the PV surplus and the storage capacities available in the system[1].

Figure 2 shows the PV yield and PV surplus, which are identical to all systems since they are the result of the yield that is predefined by the PV plant and weather and the equally predefined household electricity consumption (without heat pump). In the evaluation shown, the surplus is calculated on a per-minute basis, and shows the potential that is available for increasing self- consumption. Figure 4 shows how much of this PV surplus was fed

[1] The use of the thermal mass of the building is excluded in the presented measurements.

to the grid by the different systems that were tested. Figure 5 shows the electric energy consumption from the grid for the same systems.

With 60 kWh in total, the CombiAir-System has the highest feed-in to the grid, followed by the 2TankBrine-System (compare Figure 4). Both are systems without electrical storage and thus with a lower total storage capacity and no means for electric load shifting of household appliances.

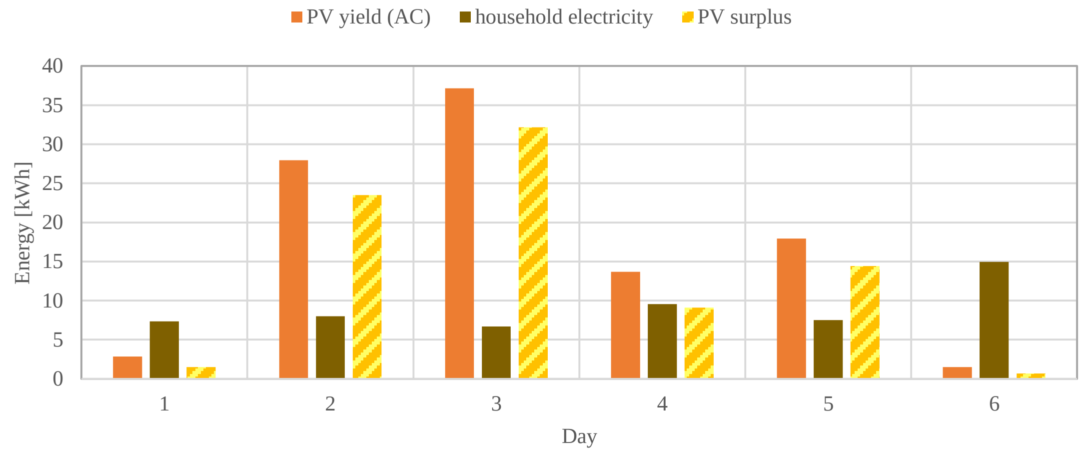

Figure 3: PV yield and household electricity and PV surplus per day. The calculation of PV surplus is based on minutes.

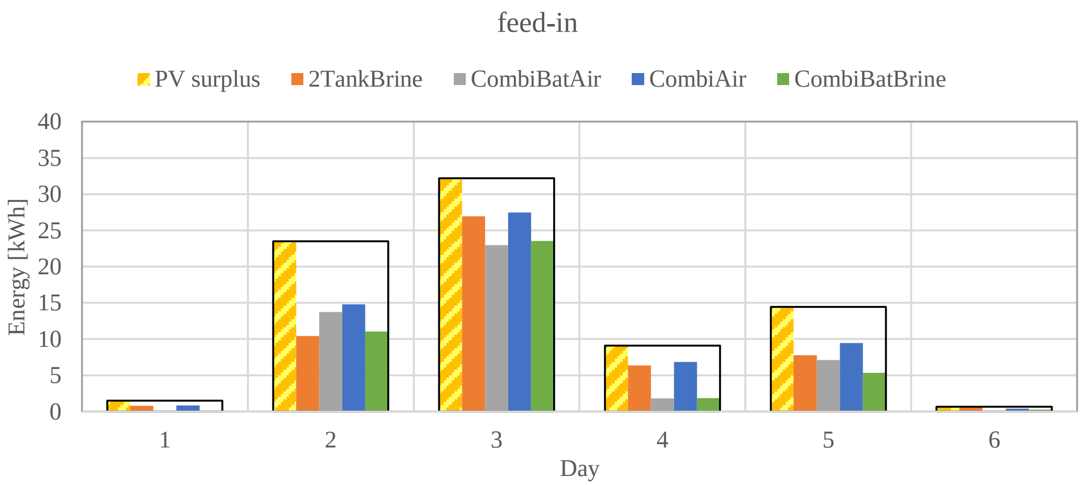

Figure 4: Electric energy supplied to the grid per day.

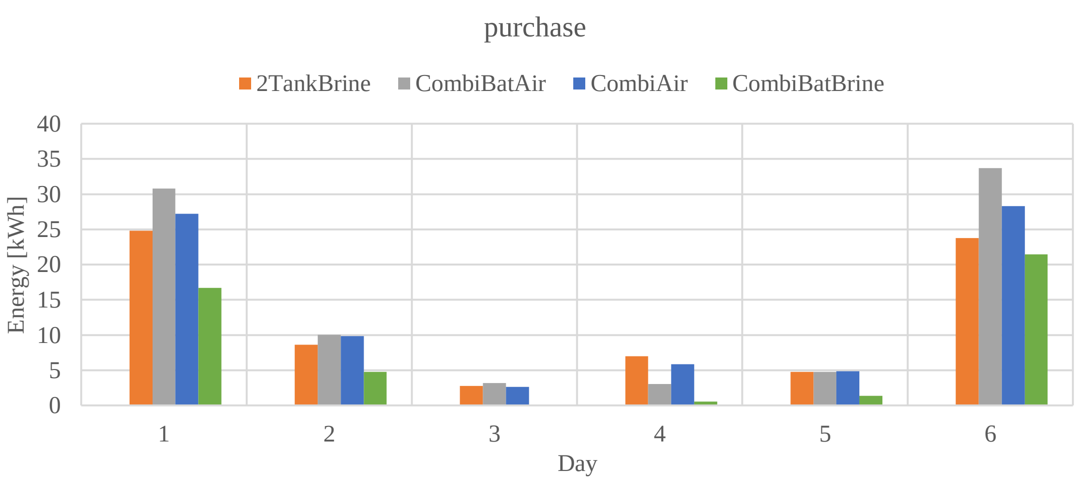

Figure 5: Electric energy from the grid per day.

The CombiBatBrine-System uses the least electricity from the grid (45 kWh in total, Figure 5). The further order is: 2TankBrine, CombiAir and CombiBatAir. It is remarkable on the one hand that the 2TankBrine-System (with brine-source heat pump) is only slightly better than the CombiAir-System (with air-source heat pump) and on the other hand that the highest value for purchased electricity from the grid results from a system with a battery.

Due to the test method, the loads of space heating, domestic hot water and household electricity are equal for all systems. For this reason, the key figures of the tested systems can be compared directly with each other. The CombiBatBrine-System reaches in all categories shown in Figure 6 the highest value: Well above 50 % in both, self-consumption ratio and self-sufficiency rate and close to 1 in PV generation ratio.

The CombiBatAir-System achieves a comparatively high self-consumption ratio. However, the self-consumption ratio increases with higher overall consumption, and the purchase of electricity from the grid was thus also highest for the CombiBatAir-System, which shows the weakness of self-consumption and self-sufficiency as KPIs.

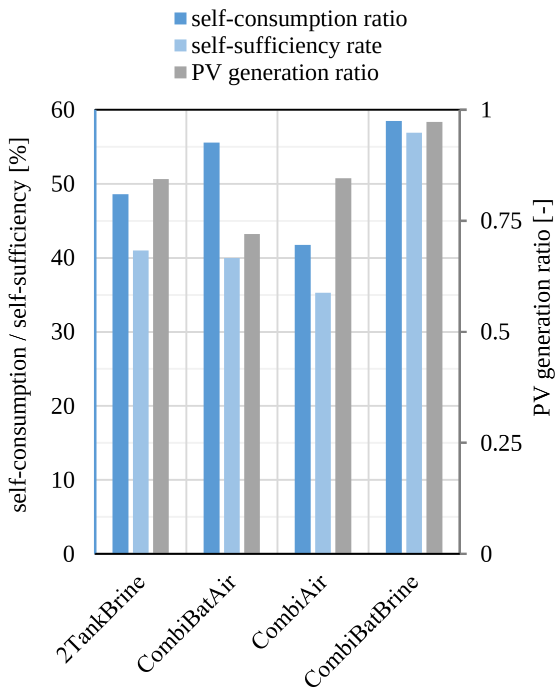

Figure 6: Operating figures of the tested systems.

The PV generation ratio was described in chapter 2. It was mentioned, that this value can vary despite an identical PV system and identical useful energy demand. The results show that the CombiBatBrine-System achieves the highest yield ratio due to its lowest total consumption. A PV generation ratio of 1 indicates a Net Zero Energy building. In this case, internal consumption and self-sufficiency must be identical. The measurements confirm this mathematical law.

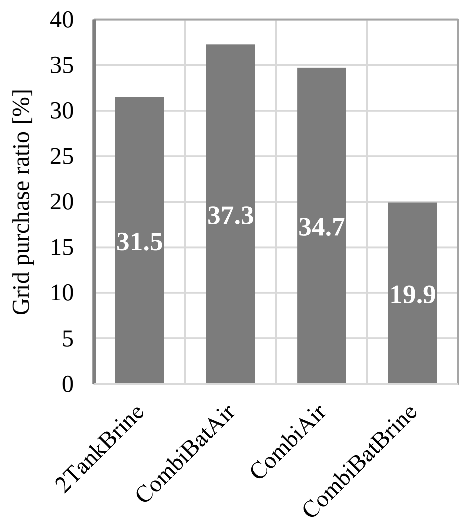

Figure 7: Grid purchase ratio of the tested systems.

Figure 7 shows another key performance factor: The grid purchase ratio. This value shows what proportion of total useful energy demand (the addition of DHW delivered, space heat delivered, and household electricity) had to be covered by electricity from the grid. This value should be as low as possible. The System CombiBatBrine achieves the lowest and thus the best value. The CombiAir system should also be noted positively in this case, since it achieves a comparatively good, i.e. low, value with relatively simple means (air-water heat pump, no battery). A grid purchase ratio of 20% means that compared to the total useful energy demand, only 20% of electricity input from the grid was necessary. With other words, the system delivered five times more useful energy than it consumed electricity from the grid.

5. Discussion

Thermal energy storages

In addition to comparing the systems with each other, valuable insights into the operating behavior of the individual systems were gained. The visualization of the temperature profile in the thermal storage tank or the power of electrical sources and sinks provide information on the quality of control strategies. Figure 8 gives an overview of the temperatures in the thermal energy storages. The highest temperatures are reached in the DHW storage tank of the 2TankBrine-System, which was to be expected. The days 2 and 3 of the test sequence are the days with the highest PV yield (and PV surplus). At these two days the average storage tank temperature reaches 60 °C. After the maximum temperature in the domestic hot water tank has been reached, the temperature in the space heating buffer starts to rise. In this way, the system achieves a very high self-consumption value without the use of a battery.

The System CombiBatBrine shows also a rise in the temperature of the combistore, but on a much lower level. The average temperature of the tank during winter days (day 1 and day 6) is around 30 °C. The maximum average temperature reaches 40 °C on days with a high solar yield. The comparably low average temperatures are the result of a good temperature stratification within the storage, since the comfort requirements for domestic hot water were always met. Figure 9 shows the measurement of electric power during the test. It can be seen that the use of PV surplus to heat the storage tank by heat pump was limited. In this case, the hydraulic system (storage tank connections and position of the temperature sensors) inhibited charging of the storage tank to a higher temperature.

The course of temperatures in the CombiBatAir-System shows that there was no temperature increase on days with high PV yield. In this system, the heat pump was not controlled according to the PV yield but only according to the heat demand.

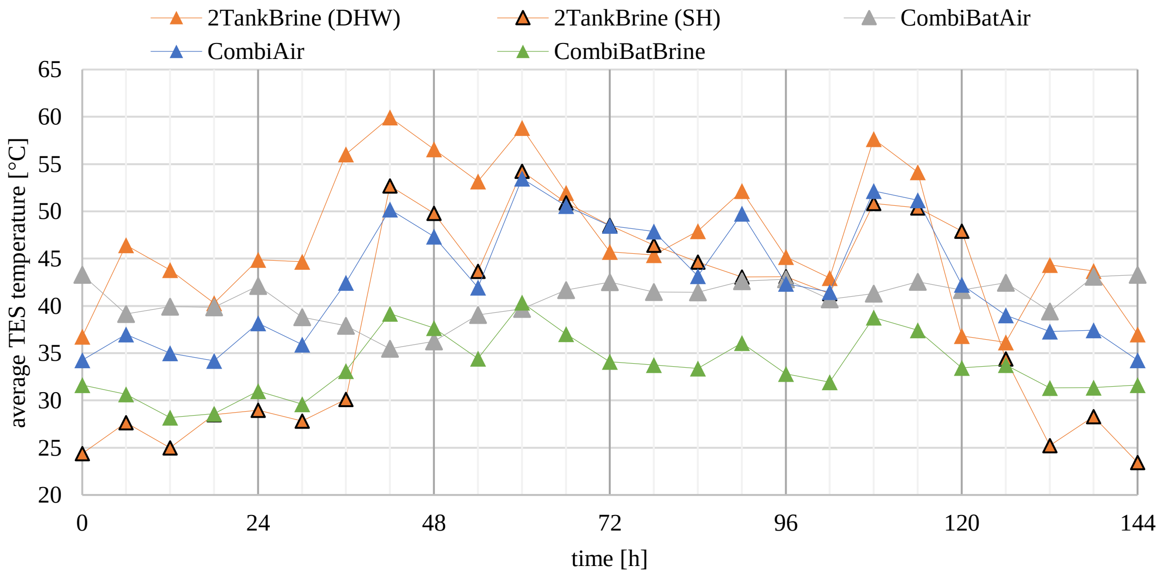

Figure 8: Average temperature of the TES-tanks during the 6-day system test.

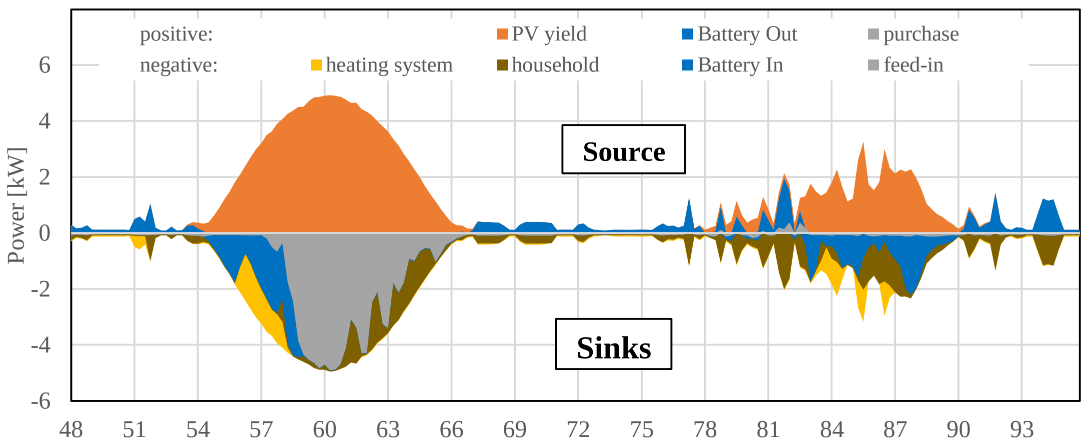

Figure 9: Excerpt of the measurement of System CombiBatBrine: Measurement of electric power during the days 3 and 4 of the 6-day test sequence.

Electrochemical energy stores

Two of the tested systems use an electrochemical storage device in addition to the thermal energy storage. The table describing the tested systems (Table 1) shows that the storage capacity of the batteries used is of a similar size.

The charging and discharging strategy of the batteries was simple: PV surplus that was not converted to heat by the heat pump is charged into the battery. As soon as the demand for household electricity and the heating system is higher than the available PV electricity, the battery is discharged again. Neither system differentiated between household electricity and the demand of the heating system during discharge.

Figure 10 and Figure 11 show the electrical power of the charging and discharging of the batteries and the cumulative energy during the 6-day test. The state of charge of the batteries has been checked on an hourly basis. It was in both cases identical at the beginning and the end of the test. It is therefore clear that the final value of the energy balance corresponds to the losses of the battery. These losses consist of the conversion losses in the inverter, the losses of the cells and a standby consumption of the battery system including its controller. The cycle efficiency of the batteries was 74% (CombiBatAir) and 65% (CombiBatBrine).

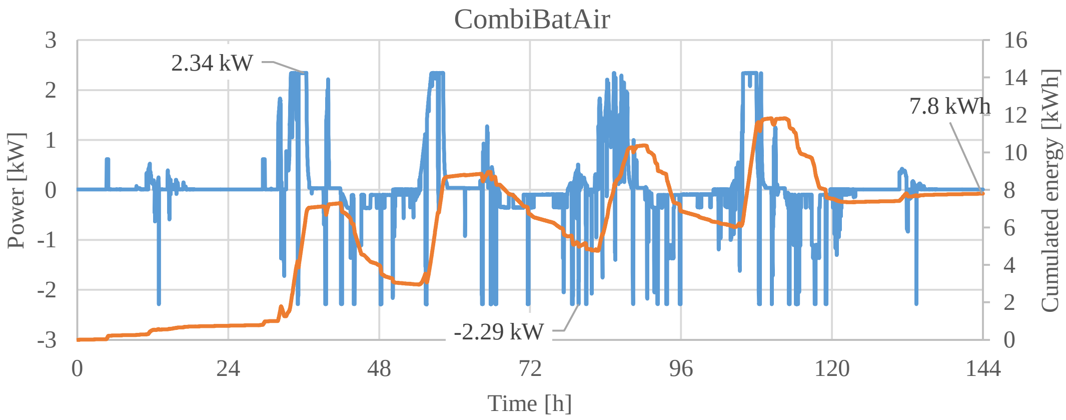

Figure 10: Electrical power of the charging and discharging of the battery as well as the cumulative energy during the 6-day test.

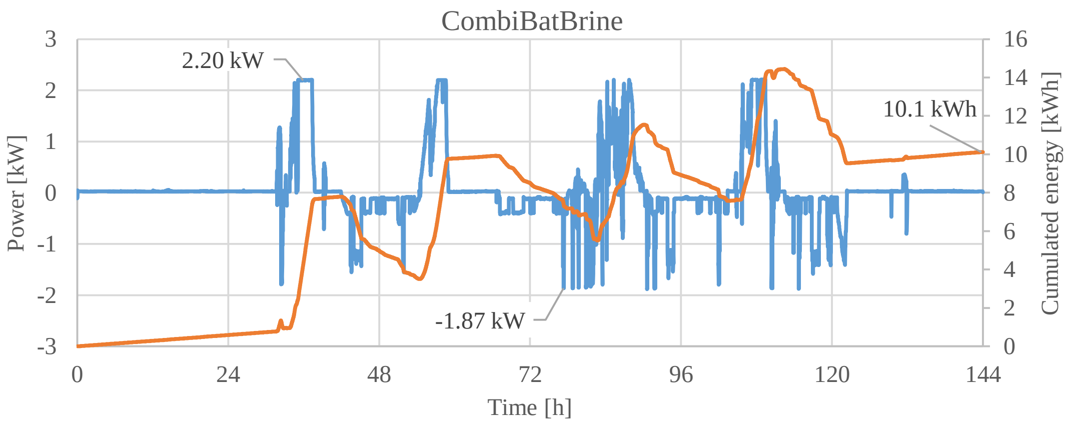

Figure 11: Electrical power of the charging and discharging of the battery as well as the cumulative energy during the 6-day test.

Benefit to the grid

The increasing use of PV systems may lead to a stress on the grid on days with high solar radiation. Heating systems with heat pumps and batteries have the potential to cut the feed-in peaks. However, these feed-in peaks are not cut with the control strategies implemented in the tested systems. Figure 12 shows exemplary for two of the tested systems that the PV power is completely fed into the grid at peak times. This is due to the fact that the storages are already full at this point in time.

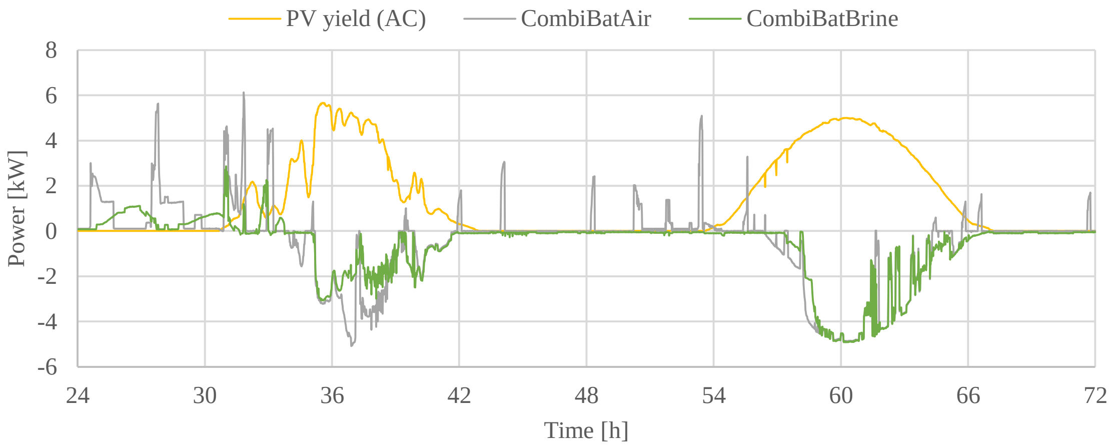

Figure 12: Excerpt of two system tests: PV yield (yellow) and the grid purchase (positive values green or grey) and feed-in (negative values) during a period of two days within the 6-day test.

Key Performance Indicators

The weakness of self-consumption and self-sufficiency as key performance indicators (KPIs) becomes apparent when electric or thermal storages are introduced with their respective losses. Losses of electric or thermal storages that are charged predominantly with PV electricity or with heat produced from PV electricity in combination with the heat pump, inevitable increase both KPIs. Therefore, a new KPI, the grid purchase ratio, has been introduced. This new KPI sets electricity purchase in proportion to useful energy demand. It has proven to be a more reliable indicator for the quality of the system and its control, and it allows for a fairer comparison of the different systems.

6. Conclusion

Test method

The whole system test method CCT proved to be a valuable tool both for system development as well as for performance evaluation. The advantage of this kind of system test is that non-ideal component interactions and the influence of hydraulics and control under transient operating conditions can be detected and evaluated precisely. The test delivers within 6 days information about all operating conditions that may occur during a whole year and is thus much faster than field testing. Compared to field testing, the amount (number of sensors installed) and precision (high precision laboratory equipment used) of information that is obtained is much higher. Moreover, the results can be compared with tests of other systems that were performed under the same boundary conditions.

Test results

The test results show that the maximum self-consumption as a target function for the control of the systems does not lead to efficient solutions. The entire energy balance must always be taken into account in the analysis. For this purpose, it is better to consider the grid purchase ratio. However, economic aspects or grid friendly operation are not taken into account with this solution either. Tariffs for energy purchases and feed-in as well as aspects of grid friendliness also play an important role for end customers and grid operators.

The evaluation of the individual systems revealed significant differences:

2TankBrine: The control of the heat pump according to the current PV surplus works very well, and higher temperatures are reached in the storage tank in this operation mode as intended. A negative aspect was the inadequate implementation of a desuperheater during space heating operation that lead to poor storage stratification and increased energy consumption in normal operation. This prevented the system from achieving a better overall result.

CombiBatAir: In this system the stratification of the combistore while being charged by the heat pump must be criticized. It lead to unnecessary high flow temperatures of the heat pump and correspondingly low efficiency. A thermal storage with good stratification behavior is essential for reaching high efficiencies in combination with a heat pump. Especially with the particularly high volume flow rates that are advantageous for heat pumps, this is a special challenge. The cycle efficiency of the battery was higher than for the other system with battery, which was mainly due to less stand-by electricity consumption.

CombiAir: Implementing the CombiAir concept in the field does not require any special investment on the part of the user: no geothermal probes or batteries are required. Although the degree of self-sufficiency of 35 % is the lowest value of the various candidates, a good value is nevertheless achieved for the grid purchase ratio.

CombiBatBrine: This system shows a very good overall behavior. Good values are achieved for most key figures. The purchase of electricity from the grid was by far the lowest. Nevertheless, there is still room for improvement: The efficiency of the battery remained below expectations. Especially the standby consumption of the battery was too high (around 24 W). The thermal storage showed a good stratification and enabled an efficient operation of the heat pump. However, the hydraulic connection missed potential for storing excess PV as heat in the storage tank.

7. Acknowledgment

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