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Towards an harmonized whole system test method for combined renewable heating systems for houses

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Abstract

The objective of this work is the development of harmonized efficiency test methods for combined renewable heating systems for houses, using a hardware-in-the-loop approach. An overview of the principles of the existing whole system test methods used by 3 research institutes involved in the project (MacSheep 2012) is given. Main objectives are realistic dynamic test sequence elaboration for solar and heat pump systems and comparison of results from tests achieved in different institutes. In order to reach these objectives, the first phase of the work aimed to harmonize the boundary conditions that comprise both the physical boundaries of the tested system as well as the climate and heat load definition, and this is presented in the first part of the article. The second part presents two methodologies to elaborate 12-days and 6-days whole system test sequences, validation results for solar and air source heat pump systems (SHP) and a methodology for achieving equal amount of space heat supplied by the tested system while at the same time providing a realistic response of the heat distribution system.

Key-words: solar combi system, air source heat pump system, dynamic test method, accelerated test, benchmark test

1. Introduction

During the past years, the research institutes CEA INES from France (Albaric et al. 2008), SERC and SP (Bales 2004) from Sweden, and SPF (Vogelsanger 2003) from Switzerland have developed dynamic test methods for complete heating systems under real-life conditions that follow similar test principles (Haller et al.2013). The main idea in these test methods was to apply realistic weather conditions for a few days on a virtual solar collector field and building and to monitor the real dynamic response of a real compact solar combisystem under those conditions. Each loop of the real system (mainly domestic hot water (DHW), space heating (SH) and collector loops) is connected to a hydraulic module. At every time step (typ. 1 min), modules record the temperature and the flow rate of incoming fluids and send these measurements to the monitoring computer. Those measurements are used as inputs to the TRNSYS simulation software. Then, according to the outputs of the TRNSYS calculation, fluid temperatures at the outlet of the modules are adjusted. This way, each module emulates every virtual component simulated by the software. Data exchanges are represented in Fig. 1.

The objective of the collaborative work in the project (MacSheep 2012) is to develop an improved dynamic whole system test method that meets some requirements:

- To be composed of a number of continuous consecutive test-days with weather conditions representative for all seasons of a year.
- To be a benchmark test whose result shows directly the ranking of different systems in terms of the annual energetic performance of these systems.
- Annual results derived from test results by direct extrapolation by multiplication of the test results by the number of days in the year, divided by the number of days of the core test sequence. The validity

of the direct extrapolation approach has been checked for systems with fuel burning devices as auxiliary heating device (Albaric et al. 2008) and the work within MacSheep project shows that this extrapolation approach could also be used for SHP systems provided the elaboration of dedicated weather test sequence.

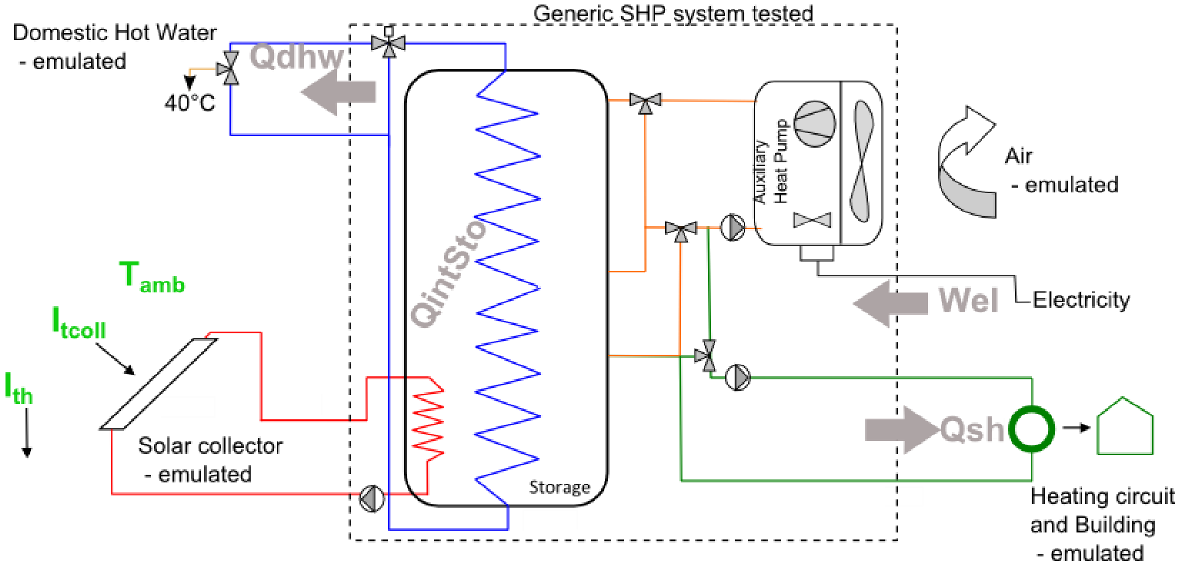

Fig. 1: Data exchange and energy flows between a real Air source SHP system and the emulated environment during a test on a semi-virtual test bench. Qdhw : energy provided to DHW preparation - Wel : total electricity consumed by the system - Qsh : energy provided – QintSto: internal energy content of the thermal storage

The test will be based on one climate and one definition of DHW and SH loads. The annual results that are obtained will a priori be valid for this one climate and load.

The final test results for the determination of the energetic performance of the systems are the auxiliary energy consumption. In the case of solar and heat pump system, the only auxiliary energy consumption is the electricity. Therefore, the benchmark can be based on the following figures of merit, either taken directly from the core test sequence or from the extrapolation to annual values:

- Total electricity consumption during the test sequence or whole year
- Ratio of useful heat output divided by total electricity consumption (performance factor)

The new harmonized boundary conditions are changing from the original test conditions from each institutes and are summarized in section 2. The improvements of the new harmonized test sequences that meet the requirements based on new test boundaries and test conditions are presented in section 3: selection of a 12-days weather arrangement test sequence for SHP systems, control of the space heating load for comparable results, and optimization of solar irradiation and outside temperature parameters of 6-days sequence for SHP systems for short duration benchmark test. Thus two possible test sequences have been derived, one with 12 test days and one with six days.

2. Harmonized boundary conditions of the test

First part of the harmonization work focused on the physical boundaries between tested system and the test bench. These are shown Fig.2. The auxiliary heater (a heat pump in this case), the storage, and all distribution pumps and valves for space heating and solar loop are part of the tested system and are taken into account for the electricity consumed by the system; for domestic hot water (DHW), the scalding valve protection or heat exchanger with pumps are also part of the tested system; all controllers and associated sensors are included in the tested system, with some installed inside the tested system itself while others have their signal emulated by the test rig. For practical reasons, the solar collector field itself is never part of the tested system since it would be unrealistic to install 10 to 20 m² under artificial sun test bench with controlled and reproducible operating conditions.

Heat traps devices are used for every hydraulic connection from the system to the test bench in order to exclude the influence of test bench hardware on the heat losses of the system.

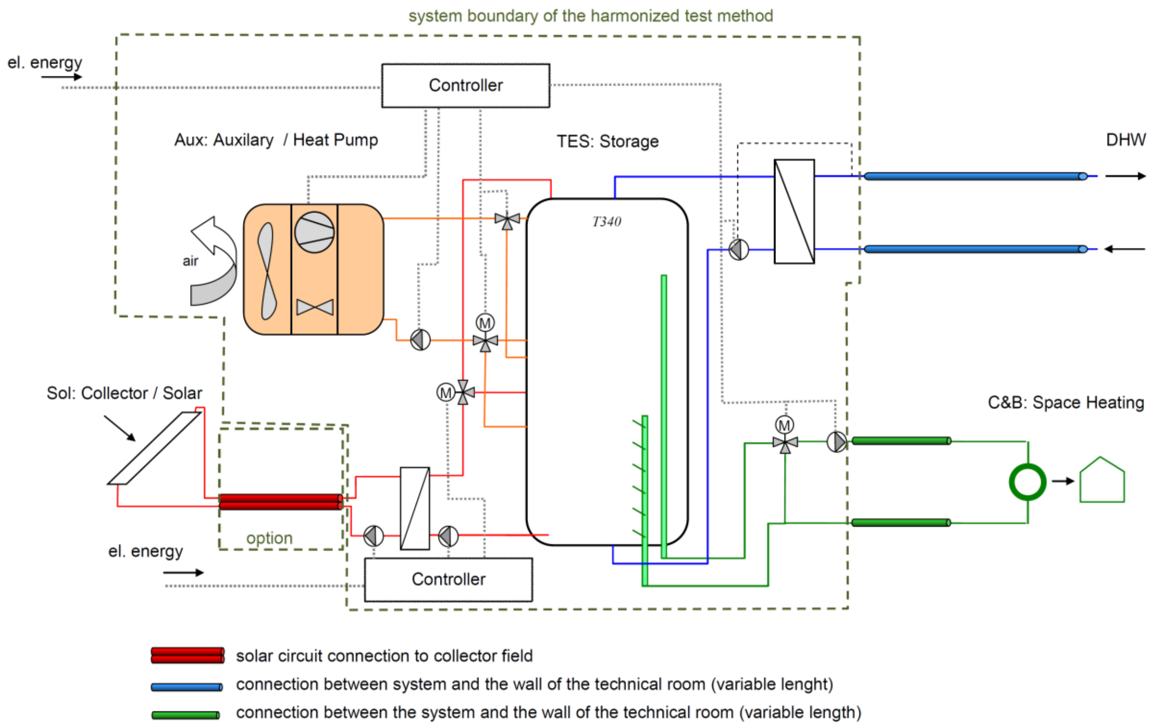

Fig. 2: Simplified hydraulic scheme showing the system boundaries where the energy balances are measured for an Air source SHP system.

Besides the test boundaries, the test conditions applied to the system that depend on time during the test sequence have been defined (weather and DHW draw-offs profiles), as well as the component models that bring it to the tested system boundaries (building, solar collector, DHW user mixing valve). A short time step of one minute was chosen for the simulation that updates the data exchange between test bench and tested system in order to get realistic dynamic behavior.

The reference weather data used is Zurich SMA weather station provided by Meteonorm. The data file CH-Zuerich-SMA-66600.tm2 is distributed in the standard European climates package within TRNSYS. Zurich SMA location is chosen since it is well known from previous research IEA SHC Task 26 and Task 32 representing a temperate European climate with significant space heating load and solar energy resource: therefore it makes possible for well-designed SHP system to achieve good performance figures for industrial companies that want to test their systems in the end.

The heating load target is the SFH045 building (SH load of 45kWh/m2/year for Strasbourg reference climate and 60kWh/m²/year forZurich climate) of the IEA SHC Task44 / HPP Annex 38 (T44A38). A new TRNSYS component based on ISO 13790 Standard (simplified building with dynamic behavior) is used with parameters derived from Type 56 building model of SFH045. The heat losses from building to the ground are related to the climate and time according to T44A38 reference system. The heating floor is chosen as heating circuit since it's widely used with both solar and heat pump systems because of its thermal inertia and low operating temperature that maximize solar collector and heat pump efficiencies. Moreover it is likely to show better performance figures for SHP product manufacturers.

Two different realistic water draw-off profiles have been chosen based on statistical distribution (Jordan and Vajen, 2005), one for the 12-day test sequence and one for the 6-day test sequence. The average number of water draws per day in this profile is 34 and the expected temperature at the outlet of user mixing valve for all of these water draws is 40°C. The user mixing valve is emulated either as a physical component (thermostatic valve set to 40°C) or the DHW flow rate flowing through the tested system is calculated from the DHW temperature delivered by the system and the expected flow rate at user end point for each timestep. The average energy drawn per day is 7.4 kWh, and the mass flows range from 300 l/h to 1080 l/h. A varying cold water temperature supply to the tested system according to Zurich SMA climate is chosen based on mains water temperature output from TRNSYS17 component Type 15.

3. Development of the test method

3.1 A 12-day test sequence for air source SHP systems

The aim of this work was to find an optimized arrangement of weather data for 12 days picked from 365 days annual data, such that performance results of ASHP reference system harmonized in MacSheep gained from the 12-day test (SH load, DHW load, and auxiliary energy consumption) can be extrapolated to annual results by the factor 365/12. This approach was applied previously by Albaric et al. 2008 to solar combisystems combined with gas boiler and has to be adapted to the harmonized boundaries defined in section 2 and to an ASHP system (hydraulic scheme is illustrated in fig.1). The chosen system was the MacSheep reference system with 10m² flat plate solar collector, 750L buffer water storage. The target function to optimize is the total electricity consumption of the whole SHP system.

The distribution of DHW draws during the 12-day test sequence draw-off profile is adapted to have a relatively large amount of energy drawn out of the tank storage from day 9 to day 12 (in order to discharge the store after the summer-like period during the test) and the total amount of the DHW load during the whole test is 12/365 of the annual DHW load. The 12-day test sequence is then the combination of a draw-off profile and weather sequence applied to the system to be tested. For the evaluation of the 12-day test sequence, a 13th day is actually necessary to initialize the system before starting to evaluate the energy flows through the system along the last 12 days: this day 0 is chosen the same as the day n.

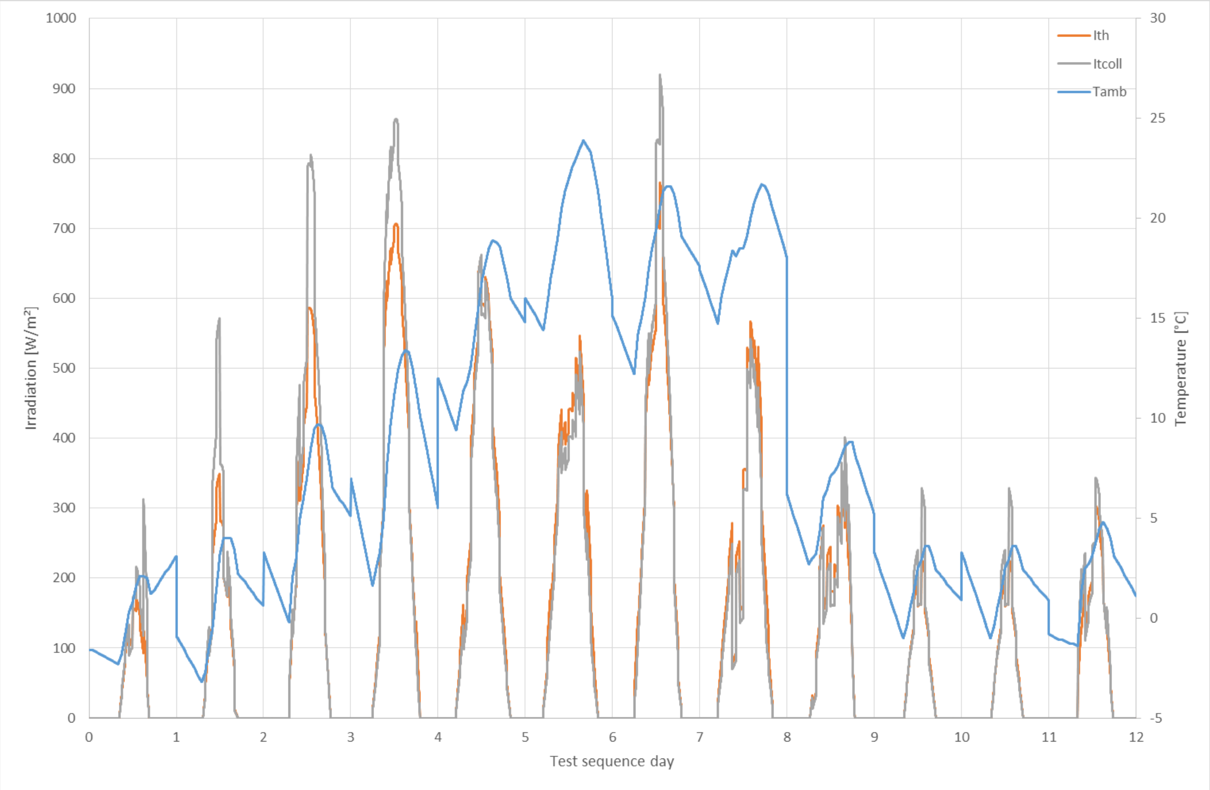

Fig. 3: Overview of the optimized 12-days test sequence

The search of optimal sequence of 13 days is achieved by a software tool that combines TRNSYS simulation of the reference system and post-processing of each iteration simulation results thanks to a custom Scilab automation and optimization module. The tool simulates once the reference system during 8760h (1 year) and calculates monthly averages and cumulated performance figures for Qsh, Qdhw, Wel, QintSto quantities (Cf Fig. 1). Annual SH demand is 8.3MWh, DHW demand is 2.8MWh and total electricity consumption is 3.8MWh. Optimization is started with an initial weather sequence of 1+12 days: these initial days are chosen to be close to the monthly average values of ambient air temperature (Tamb), total irradiation on horizontal plane (Ith) and total irradiation on collector plane (Itcoll) of the annual simulation. Then the algorithm simulates the 13 days of the test sequence: daily averaged values for Qsh, Qdhw, Wel, QintSto quantities are calculatedfor the 12 days. Then the tool calculates deviations between monthly averaged values and test sequence extrapolated (multiplied by 365/12) values and uses it to search for days within the yearly weather database with modified characteristics for Tamb, Ith and Itcoll. The 12-day weather test sequence that best matches these weather target characteristics are then simulated and its performance is evaluated again against annual performance figures: the algorithm iterates first for selection of day 1 then moved to next day until day 12. If day 12 is changed from initial value, the selection process starts selection of a new improved day 1 otherwise the selection process is stopped. It required typically 400 simulations of the 12-day test sequence to converge to a reasonable solution among the 12^{365} possibilities.

These simulations led to the final selection of a best candidate 12-day weather test sequence that shows 1% deviation of the total electricity consumption while the SH and DHW load deviations are below 1%. An overview of this weather test sequence is represented in Fig. 3.

The reliability of the resulting 12-day test sequence is investigated with a number of variations of the system configuration: so called “4-pipes” and “3-pipes” hydraulic scheme (connection between the heat pump and the solar combistore that respectively improves or decreases the stratification within the store), increased solar collector area, thermal energy storage volume, effective vertical thermal conductivity of the store (store destratification effect variation) and overall performance of the heat pump (changes in compressor and heat exchanger efficiencies).

Tab. 1: Validation: overview of the deviations between annual and extrapolated by 365/12 performance figures with regard to variation of system configuration

Store connect-ions	Store therm. cond. (W/m.K)	Overall HP perf. variation	Coll. area (m2)	Store capacity (L)	Wel	SH	DHW	SPF+
4-pipes	0.6	-	10	750	-1.0%	0.0%	-0.9%	0.8%
4-pipes	0.6	-	15	1000	-3.0%	0.0%	-0.9%	2.9%
3-pipes	0.6	-	10	750	-1.0%	-0.2%	-0.9%	0.7%
3-pipes	0.6	-	15	750	-1.8%	-0.2%	-0.9%	1.5%
3-pipes	0.6	-	15	1000	-1.4%	-0.2%	-0.9%	1.0%
4-pipes	0.3	-5%	10	750	-1.9%	-0.8%	-0.9%	1.1%
4-pipes	0.3	-	10	750	-2.3%	-0.7%	-0.9%	1.6%
4-pipes	0.3	+5%	10	750	-2.2%	-0.8%	-0.9%	1.4%
4-pipes	0.6	-5%	10	750	-1.6%	-0.8%	-0.9%	0.8%
4-pipes	0.6	-	10	750	-2.1%	-0.8%	-0.9%	1.3%
4-pipes	0.6	+5%	10	750	-2.7%	-0.8%	-0.9%	1.9%
4-pipes	1.2	-5%	10	750	-2.5%	-0.8%	-0.9%	1.8%
4-pipes	1.2	-	10	750	-2.8%	-0.8%	-0.9%	2.0%
4-pipes	1.2	+5%	10	750	-3.7%	-0.8%	-0.9%	3.0%

The validation results (Cf. Tab. 1) shows deviations between the annual and extrapolated values below 4% for total electricity consumed by the system and below 3% for the SPF+. While it is not the focus in MacSheep project, further investigations using this tool would be possible to elaborate a 12-day test sequences that would allow direct extrapolation of 12-day test with different climate and building combinations. In addition this 12-day test sequence provides enough test data to train and validate a neural network model of the whole system tested similarly to Leconte 2012 and Lazrak 2014.

3.2 New method for realistic space heat distribution behaviour and comparable load

Existing approaches to deal with space heat distribution

The existing test methods for complete heating systems apply different approaches to deal with space heat distribution:

- In order to have an identical heat load for all systems tested (the same heat delivered to the building at each time step) a load-file is used for the building space heating. The advantage of this procedure is that each system delivers the same amount of heat to the building which is considered to be a must for a benchmark test. There are two disadvantages with this procedure: first, the heat distribution system (i.e. the space heat distribution pump, the mixing valve and the control of these) is not part of the tested system but emulated by the test rig. For solar and heat pump systems, it is expected that these components and their control may influence the performance of the system quite substantially. The second disadvantage is that a control mechanism has to be implemented to assure that not only the amount of heat delivered corresponds to the heat load from the file, but that at the same time the supply temperature is high enough for transferring the required amount of heat with the given heating system and room temperature (comfort requirement).
- The tested system is allowed to deliver heat to the building according to its own control. A simulation and emulation of the building is used to determine the response of the space heat distribution and building in order to assure that the response is realistic. This procedure has the advantage that it allows the tested system to do what it normally would do in a real case, and it is also possible to let the system run on hot water priority (pausing heat delivery to the building during a scheduled time slot). The comfort requirement is that the simulated room temperatures must not fall below a given threshold and is thus easy to implement. However, this method has the drawback that it leads to different amount of space heat supplied by different systems and thus it it difficult to compare and interpret results (see Haberl et. al. EuroSun 2014) and not suitable for a direct benchmarking.

Both approaches have obvious advantages and disadvantages. None of the two approaches achieved the desired identical heat load for different tests while at the same time letting the system use their own space heat distribution hydraulics and control.

New combined approach to deal with space heat distribution

The new approach uses daily energy targets and an online building simulation at the same time and works as follows:

The tested system is allowed to deliver heat to the building according to its own control strategy. For this purpose, the candidate gets the actual ambient temperature of the test sequence. With the help of an online building simulation, the response of the heat distribution system and the room temperature in the building is calculated and emulated. The emulation includes the return temperature of the heat distribution system and the thermostatic valve of the heating. The thermostatic valve is emulated by a motorized valve that gradually closes and thus reduces the mass flow rate in the heat distribution circuit when the simulated room temperature is increasing from 20 to 22 °C.

The energy that is delivered to the building during the test is compared on a daily basis to pre-defined 24 h load-files. The pre-defined load file represents the energy that is necessary to keep the room temperature at 20 °C (energy target). In addition to this ideal heat delivery is also the maximum energy defined, that is allowed to be delivered to the building without a reaction. This maximum energy is defined as the ideal heat delivery plus a maximum excess. The maximum allowed excess is 4 kWh or more than 10 % of the daily target and is gradually reduced to zero within the last three hours of the test-day.

The tested system has to deliver enough energy to the building to keep the room temperature above 19.5 °C. When the temperature drops below this threshold, the test has to be started again with adapted parameters (e.g. a steeper heating curve). When the daily energy that is delivered to the building exceeds the maximum allowed heat delivery, the heat supply will be restricted in order not to exceed the target by means of a motorized valve in the heat distribution system.

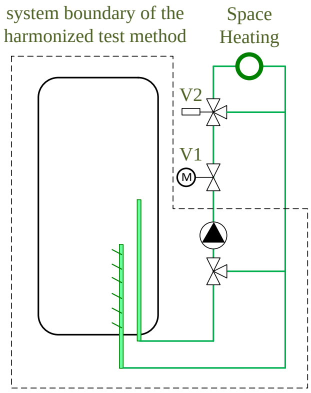

Fig. 4: Space heating loop in system testing.

The combined approach to deal with space heat distribution was successfully tested during a whole system test. On the test bench there are two valves necessary (compare fig. 4): One motorized valve to emulate the thermostatic valve, which is in addition used (enhanced) to restrict the heat supply to the building (V1).

Because some heating systems don't allow closing the heat distribution system completely (in order to avoid high pressure disruption of the compressor) is a second valve necessary that emulates an overflow valve (V2). When the heat distribution to the building has to be prevented (because the final energy target of the respective test day is reached) this bypass will be opened to return the flow temperature to the system without extracting heat from the flow.

Figure 5 illustrates the progress of the test on day 12 of the 12-day test sequence. It shows the energy target and the target with the maximum allowed excess. The difference between them is reduced to zero at the end of the day. In phase "A" of the test, the actually delivered energy is below the target with the maximum allowed excess. Hence, the motorized valve on the test bench emulates only the thermostatic valve. In phase "B" of the test, the actually delivered energy exceeds the maximum allowed excess. Hence, the motorized valve restricts the mass flow further than it would be restricted with the room-temperature-criteria alone. When the final target of the day is reached (compare phase "C"), the valve closes completely and disables a further heat supply to the building.

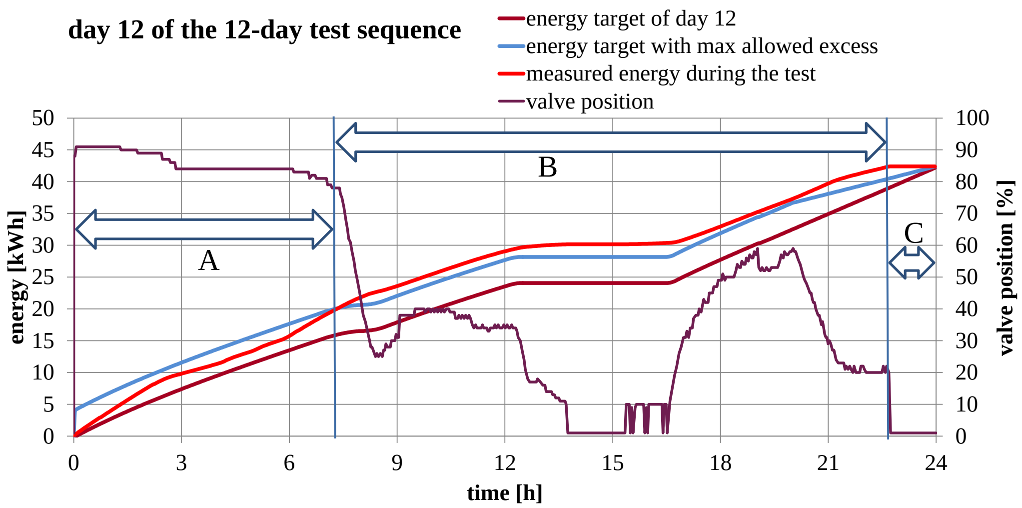

Fig. 5: Pre-defined and actually delivered energy at day 12 of the 12-day test sequence.

3.3 Development of short 6-days test sequence

The effort and cost of the system test can be significantly reduced by using a shorter test sequence than 12 days. The test method for solar combistores developed by Bales (2004) and then further developed to test solar and pellet heating systems by Dalenbäck et al., (2011), Pettersson et al., (2011) and Persson et al., (2012) is the start point of the work developing such a sequence. The order of the days was reorganized in order to start and stop the sequence with a winter day. In order to achieve a similar charge status of the system in the start and in the end of the evaluation period the initial sequence should consist of the last two days of the sequence which is already implemented in the CCT and SCSPT test methods (Albaric et al., 2008; Vogelsanger, 2003; Haller and Vogelsanger, 2005; Haberl et al., 2008). No efforts have been done trying to reduce the number of initial days for conditioning of the system to less than 48 hours.

The hot water load profile is based on a selection of the days used in the CCT test method. Solar collector gains are highly dependent on the DHW-load during spring and summer. In order to achieve the same solar gains in annual simulation and that derived from the six day test sequence the order of the chosen days had to be adjusted so that a reasonable amount of hot water is discharged during the summer days. A high DHW draw off is applied in the end of the last test day and also at the end of the two initial days in order to"force" a start of the auxiliary heater (heat pump or boiler) and thereby get a similar charge status of the system in the beginning and at the end of the six day test sequence. Day five also has a high load in order to discharge the store before the winter day. The thermal capacity of the heat distribution system (floor heating) was reduced to the capacity of a radiator in order to avoid the high time lag between energy being charged in to the floor and energy being emitted from the floor into the building.

System simulations have been used for calculating both the system's annual performance and the performance during the six day sequence. The results from the six day sequence were extrapolated to annual data by multiplying by 365/6. The daily outdoor air temperature and solar radiation was adjusted by the generic optimization program GenOpt (Wetter, 2011) in order to minimize the deviation (objective value) between the six days simulation and the annual simulation. The objective value was calculated as

$$Objective=|Wel_{6day}-Wel_{year}|+|Wcoll_{6day}-Wcoll_{year}|+|Wheat_{6day}-Wheat_{year}| \quad (1)$$

where *Wel* is the total electricity used, *Wcoll* is the energy delivered by the solar collector to the store and *Wheat* is the heat delivered to the floor heating system (heating demand).. The parameters varied were coefficients multiplied with solar radiation and coefficients (positive or negative) added to the outdoor temperature. The Air to water heat pump system developed within the MacSheep project, as illustrated in Fig.1, was used as the system in the study.

Short 6-days test results and discussion

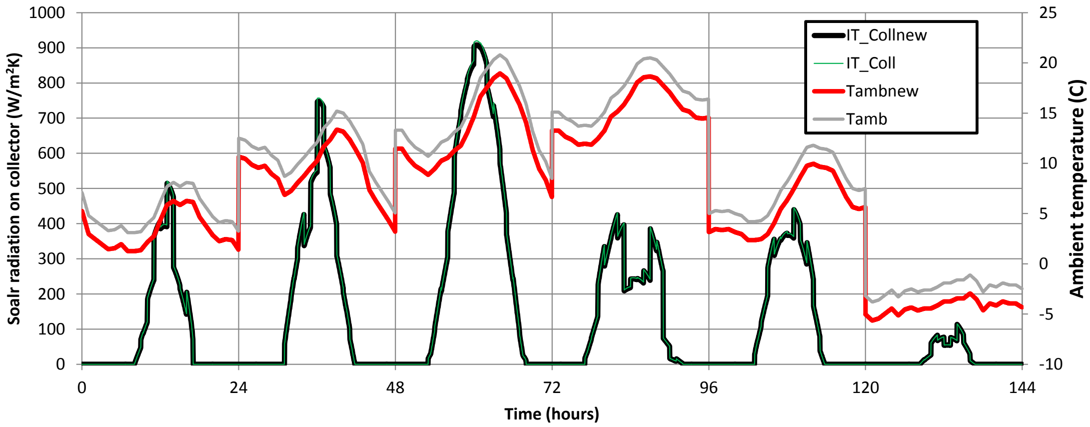

Fig. 6: The ambient temperature (Tamb) and solar radiation on collector plane (IT_coll) for the applied six day test sequence before and after the optimization called new).

The weather conditions before and after (labelled "new") the optimization runs is presented in Figure 6. The radiation level is only slightly reduced, but the ambient temperature is reduced significantly in order to achieve a better fit with heating demand and electricity consumption. The deviation in electricity demand is -2.3 %, Deviation in heating demand is 0.3% and the deviation in solar collector gains is 1.4 %. An exact fit with Electricity demand could not be achieved as the solar gains were part of the objective. Improving the objective requires further modifications of the DHW-profiles as the spring and summer DHW-load has a strong influence on the amount of solar gains.

Tab. 2: Validation : overview of the deviations between annual and extrapolated by 365/6 performance figures with regard to variation of system configuration for the six day sequence.

Store connect -ions	Store therm. cond.	Overall HP perf. variations	Coll. area	Store volume	Wel	SH	DHW	SPF	Charge status store
	kJ/h.m.K		(m2)	(l)					(kWh)
4-pipes	2.16	0%	10	750	-2.3%	0.3%	0.2%	2.6%	-1.3
4-pipes	2.16	0%	15	1000	-9.1%	0.3%	0.2%	10.3%	-1.2
3-pipes	2.16	0%	10	750	-0.3%	0.3%	0.2%	0.6%	0.5
3-pipes	2.16	0%	15	750	-2.9%	0.3%	0.2%	3.3%	0.3
3-pipes	2.16	0%	15	1000	-7.8%	0.3%	0.2%	8.7%	-0.1
4-pipes	1	-5%	10	750	2.6%	0.3%	0.1%	-2.2%	-0.1
4-pipes	1	0%	10	750	0.9%	0.2%	0.2%	-0.6%	1.4
4-pipes	1	5%	10	750	1.0%	0.2%	0.2%	-0.8%	1.5
4-pipes	2.16	-5%	10	750	-2.9%	0.3%	0.2%	3.2%	-1.6
4-pipes	2.16	0%	10	750	-2.3%	0.3%	0.2%	2.6%	-1.3
4-pipes	2.16	5%	10	750	-1.4%	0.4%	0.2%	1.8%	-0.5
4-pipes	4	-5%	10	750	-0.5%	0.2%	0.2%	0.7%	0.1
4-pipes	4	0%	10	750	0.8%	0.3%	0.2%	-0.5%	1.0
4-pipes	4	5%	10	750	-0.3%	0.2%	0.2%	0.5%	0.2

The parametric study of the influence of different system design parameters is presented in Table 2. The parameters causing the highest deviation between the extrapolated six day simulation results and the annual simulation results are related to system size. Otherwise system modifications related to system design is quite well estimated by the six day sequence, with deviations below 3% for the annual electricity consumption (Wel). Further optimization of the solar radiation and temperatures using several system sizes may improve the results for large systems. Also the DHW-load may need further adjustments to improve correlation with different system types.

The heavy floor construction causes large deviation in energy emitted to and from the floor on a daily basis. Therefore this test sequence was developed assuming a light construction. It is not possible to include the high thermal lag of a concrete floor in such a short test sequence unless the heat demand is restricted and actively controlled to a certain value for each day.

4. Conclusion

This collaborative experience led to harmonization and improvement of the most significant aspects of dynamic system testing boundary conditions that are influencing the system performance. Actually it will allow comparing the test results in the different institutes ensuring equal space heating and DHW loads during the test. The extrapolation to SHP systems annual results from test results using the 6-days or 12-days weather test sequence lead to comparable satisfactory results (Cf Tab. 1 and Tab. 2) for different system sizes and for different hydraulic solutions. The 6-days test sequence combined with the controlled space heating load method will provide a reduced duration test for benchmark purposes while the longer 12-days test sequence will additionally allow whole system model identification based on neural networks. The final definition of the harmonized test sequence will be done in October 2014 with the final results of on-going study that combines SHP and other heating system architectures for the optimization of the 6-days weather test sequence. Each institute will test a prototype of an SHP system until 2015 and get experience in the application of the harmonized test sequence.

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