# Report on improved whole system test method application experience

Deliverable 8.4 – Final – 15 February 2016

MacSheep - New Materials and Control for a next generation of compact combined Solar and heat pump systems with boosted energetic and exergetic performance

Dissemination Level: PU - public

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The research leading to these results has received funding from the European Union's Seventh Framework Programme FP7/2007-2011 under grant agreement nº 282825 – Acronym MacSheep.

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# Executive Summary

Within the MacSheep project, whole system test methods were not only harmonized between three testing institutes, but also further developed and improved. In the last phase of the MacSheep project in 2015, these improved whole system test methods were used for the determination of the performance of systems that were developed within the project. This Deliverable summarizes the experience with the application of the new improved whole system test methods.

The improvement and harmonization of the methods within the MacSheep project included:

- harmonized physical boundaries for the tested system
- shorter test sequence of six days, validated for direct extrapolation
- method for assuring identical heat load for space heating for all tested systems
- harmonized DHW profiles and tapping procedures
- concise cycle approach for assuring negligibility of changes in stored energy over the test sequence

Some of the new features posed difficulties in their implementation that had to be overcome within the timeframe of the MacSheep project. Once successfully applied, the experience with these new features was very positive. The method for assuring a pre-defined heat load for space heating as well as for useful domestic hot water supply for each day of the test proved to be reliable, and also the concise cycle approach worked as intended.

Furthermore, and most importantly, the determination of a benchmark result for the performance of solar and heat pump systems was successful. In particular, the difference between the annual key performance figures determined based on direct extrapolation of the whole system test results and annual figures derived from calibrated annual simulation results were low (5-8 %), despite the fact that the systems included features for which the method was not previously validated. These features were e.g. direct PV use for the electric supply of the heat pump and collector heat use for the evaporator of the heat pump,

One feature, the real-time calculation of penalties for not meeting comfort temperatures for domestic hot water after 10 seconds of tapping, could not be introduced by all partners due to restrictions of the test bench hardware. This feature was thus excluded from the common evaluation and reporting. However, it is still believed that this feature is important and should be introduced later in order to ensure a fair treatment of different systems with different comfort capabilities. Further work might include additional test sequences for the determination of the DHW discharge volume, as well as a short test cycle for the determination of heat losses with reduced uncertainty (less turnover of energy compared to the amount of heat losses).

Results based on component testing and system simulations obtained in phase 3 of the project were in many cases quite different from the system test results, and many control problems and difficulties of system hydraulics did only appear once the system was tested as a whole. Therefore, the whole system test method shows significant advantages over approaches that are based on component testing and system simulation only, while at the same time being less time consuming and more straightforward. Calibration of a system model using data from whole system testing and subsequent annual simulation was found to be a very time consuming process. However, this process can be spared now with the approach of direct extrapolation that was tested successfully within the MacSheep project.

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# 1 Introduction

The last phase of the MacSheep project in 2015 focused on demonstration of the solar and heat pump (SHP) systems developed across the previous stages since 2012. The performance of the built solar and heat pump systems is derived from dynamic whole system tests as reported in Deliverable 8.3 (Chèze et al. 2016). In parallel to the industrial prototype development, the development of the dynamic Whole System Test (WST) method itself was required to harmonize and improve the methods that were previously applied in the different testing institutes.

This deliverable documents the experiences gained with the new harmonized whole system test methods, and draws conclusions that are relevant for the further application and possibly further development of these methods.

In chapter 2 of this report some crucial aspects of the improved test method and the experience gained with these improved methods are highlighted, whereas in chapter 3 the direct extrapolation of test results is validated. The last section deals with the practical experiences and lessons learnt by the institutes through the testing of MacSheep prototypes.

# 2 Harmonized test method

When the project started in 2012, the research and test institutes CEA INES in France, SERC in Sweden, and SPF in Switzerland were already performing whole system tests that followed similar, but yet different, methodologies (see Haller et al. 2013). These institutes developed a harmonized and improved test method within the MacSheep project. The full description of the test method is reported in Del. 2.4 (Haberl et al. 2014), and a shorter description is presented in Chèze et al. (2014). The main harmonization steps and the experiences with these new methods are highlighted hereunder.

## 2.1 Physical boundaries of the tested system

The different system boundaries for testing that were reported in Haller et al. (2014) have been harmonized to the system boundaries shown in Figure 1.

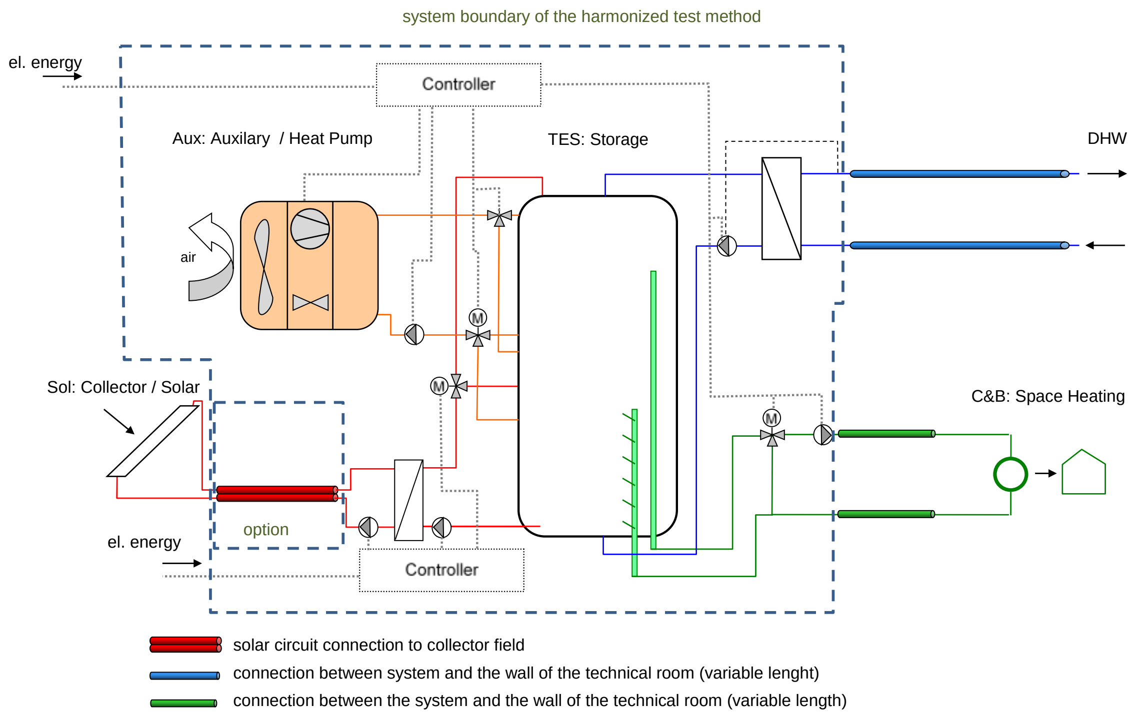



*Figure 1: Simplified hydraulic scheme showing the system boundaries where the energy balances are measured.*

These new system boundaries have been applied for the testing of the MacSheep systems in all three test institutes. One of the three tested systems included a PVT collector, and thus also a PV emulator (PV-panel is outside of the tested boundary) had to be installed. A solution for the points of measurement and system boundaries concerning electric energy supply units had to be defined, and this will also have to be harmonized in the future.

## 2.2 6-days dynamic test sequence

The 12 days test sequences and the six day sequence that were used in the three institutes before the MacSheep project were replaced with a new 6 days test sequence (Figure 2) that has been validated for the direct extrapolation of results to annual values for the case of solar thermal and heat pump systems. The new test sequence is based on continuous, realistic, consecutive test-days with weather conditions representative for all seasons of a year. This shorter test sequence and the possibility for direct extrapolation of results without the necessity of model fitting and simulation leads to a considerably less expensive and more attractive test for industrial partners. The cost for the whole procedure are more or less cut in half by this new approach.

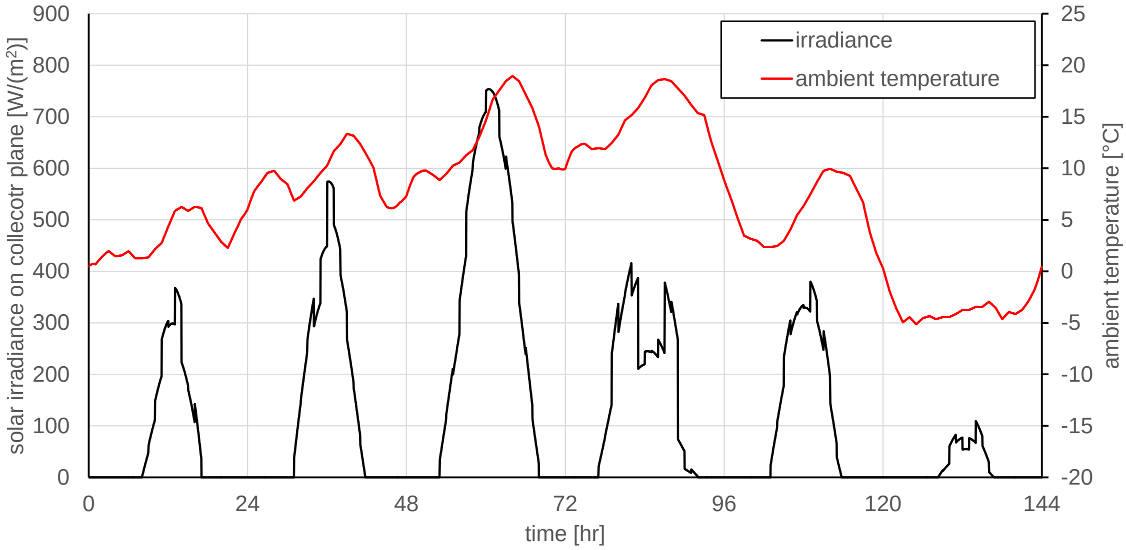



*Figure 2: The ambient temperature and solar irradiance on the collector plane for the 6-day test sequence.*

The new test sequence was successfully applied in all three test benches.

## 2.3 Boundary conditions for climate and building

The boundary conditions for climate, domestic hot water (DHW) draw-off and space heating (SH) demand were revised, harmonized, and based on publicly available models and data. A new building model was implemented in TRNSYS according to standard EN ISO 13790:2008. The set of parameters for this new model was defined for SFH45 and SFH100 of the IEA SHC Task 44 (Dott et al. 2013), which gives a heat load of 60 kWh/(m$^2$a) for the SFH45 if placed in the chosen reference climate of Zürich.

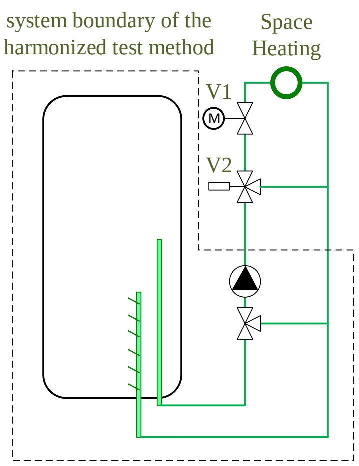
The 6-days time series are provided as text files. Climatic data is derived from Meteonorm Zurich SMA weather data. The DHW data is derived from statistical DHW data generator DHWcalc, and the fixed space heat load data were derived from simulation of SFH45 and SFH100 buildings heating demand under 6-days test sequence climate.

The heat emitters simulated are low temperature and low inertia radiators. A common standard for the simulation and emulation of the heat distribution system was not found and remains the topic of further improvement and harmonization of the test method. For the time-being, a simple radiator model has been used and parameterized for a low temperature heat distribution system.

## 2.4 Identical space heat load

One of the most important improvements of the method within the MacSheep project was achieved by finding a solution for the space heat load that leads to identical amounts of heat delivered to the space heating for different systems on the same test day, while still including a quite realistic behavior of the space heat distribution. This behavior includes the dependency of heat input into the building on supply temperatures and flow rates, as well as an evaluation of the simulated room temperatures.

Figure 3 shows the required hydraulics (left) to control the space heat delivered to the simulated and emulated radiators. The heat input can be limited by controlling, in addition to the return temperature, valve V1 that restricts the flowrate or completely shuts it off. The right side of Figure 3 illustrates the effect of this control on the space heating energy delivered for the last day of the test sequence. While the system tends to provide excess energy to the building, the control actually acts to keep it at the desired level by reducing gradually the flowrate in the space heating loop. In phase A the actual delivered energy is within the desired range whose upper limit is shown by the blue curve. During this time the valve is used as a thermostatic valve, only dependent to the room temperature of the simulated building. In phase B, when the delivered energy exceeds the upper limit allowed, the motorized valve restricts the mass flow further than it would be restricted according to a thermostatic valve only. When the final target of the day is reached (phase C), the valve closes completely and disables a further heat supply to the building.



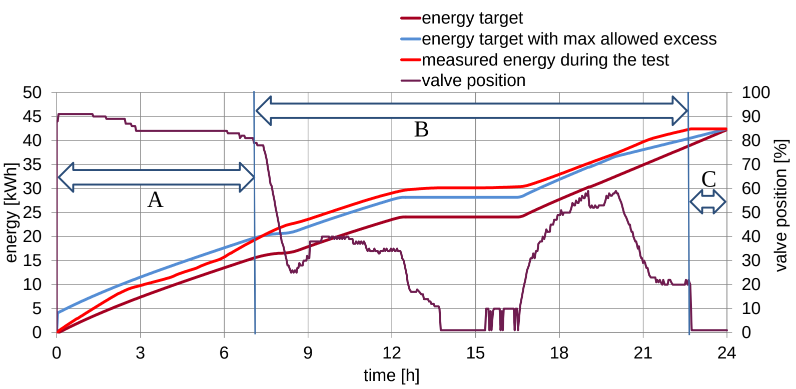




*Figure 3: Test bench valves for the space heating load control approach (left) and illustration of the progress on a test day (right).*

This new approach has been implemented by the three institutes that performed whole system tests. In the third institute CEA INES, the bypass V2 valve was not implemented: in this case, while the V1 valve is used to reduce extra heat delivery, it should never be shut completely to prevent equipment injury: it was thus not possible to reach exactly the desired amount of heat input to the building in the test reported from CEA INES. The institutes SERC and SPF applied the method successfully with a heat load of an SFH45. Figure 4 shows the space heat energy during the test at the institutes SERC and SPF. On the one hand, it can be seen that the daily energy targets were exactly reached. On the other hand, it was discovered that the two institutes did not use exactly the same predefined heat loads. Consequently, two conclusions can be drawn:

- The approach has proven its effectiveness to reach identical heat loads.
- The load profiles applied at SERC and SPF were not completely identical, and it must be decided with which of the two load profiles further tests will be done.

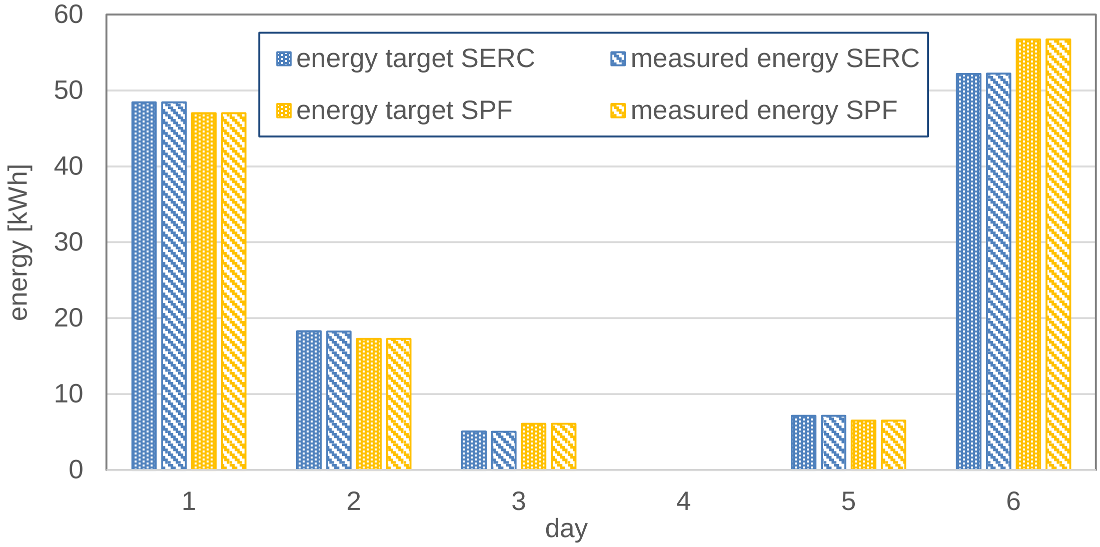



*Figure 4: Space heating load during the tests at the institutes SERC and SPF.*

## 2.5 Realistic DHW tappings

Figure 5 shows the boundaries of the tested system regarding DHW. In order to draw-off the desired energy in each draw-off event that is defined in the DHW load file, the draw-off energy needs to be monitored in real time in 1 second intervals, and DHW flow rate is switch off as soon the desired energy is reached. This was not possible in the case of SERC, where intervals could not be made shorter than 6 seconds.

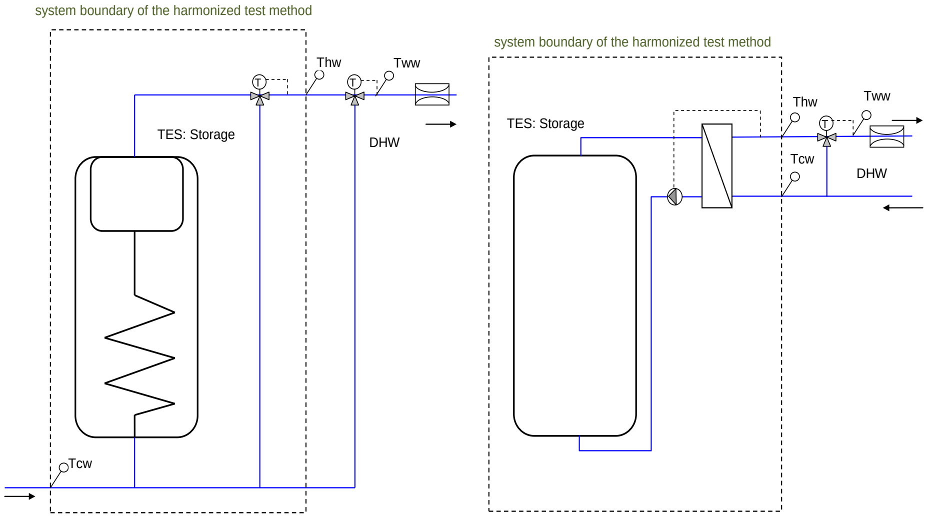



*Figure 5: Hydraulic scheme of the draw off loop showing the boundaries between the tested system and the test bench.*

Unlike for space heating, the energy drawn for domestic hot water can differ between the tests. The reason is that a domestic hot water tapping usually starts with a temperature that is not sufficiently high to cover the comfort requirements of a user. The energy that was drawn below the set point is treated as "non useful" energy. The total amount of energy drawn for domestic hot water consists of both, the useful and the non useful energy (compare Figure 6).

However, while this is the reason for the differences observed between the measurements at SPF HSR and at SERC, it cannot explain the large differences between these two measurements and the measurements that were performed at CEA INES. Again, as for the space heat load, the reason for the different domestic hot water load at INES can be found in the faulty operation of the tested system. But in addition to this, also the draw off profile that was used differed to the profiles used at SERC and SPF.

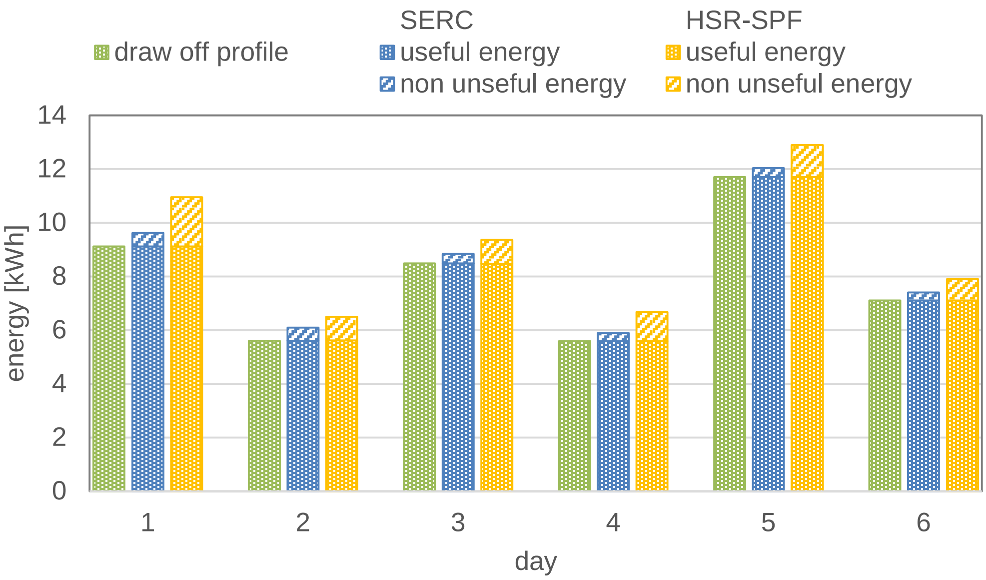



*Figure 6: Domestic hot water load during the tests at the institutes SERC and SPF.*

## 2.6 Concise cycle and "zero" energy storage

A "concise cycle" is achieved if the heat and electricity transfer measured at the system boundary is nearly identical for two days with the same "ID", i.e. for a day that is already running for the second time because of the cycling nature of the test procedure. If this criteria is met it can be assumed that the energy stored in the system at the start and at the end of the corresponding cycle is identical. Figure 7 shows three different possibilities for the evaluation of the cycling test sequence. Depending on the first time a "recycled" day produces the same results as before, the evaluation of the test is based on sequence "A", "B" or "C". This means also that a minimum of eight days is always needed to perform the test: one day for pre-conditioning, one day that could possibly be the first day of the cycle, and one "post-cycle" day for verification that the previous day with the same "ID" was the first day of a concise cycle.

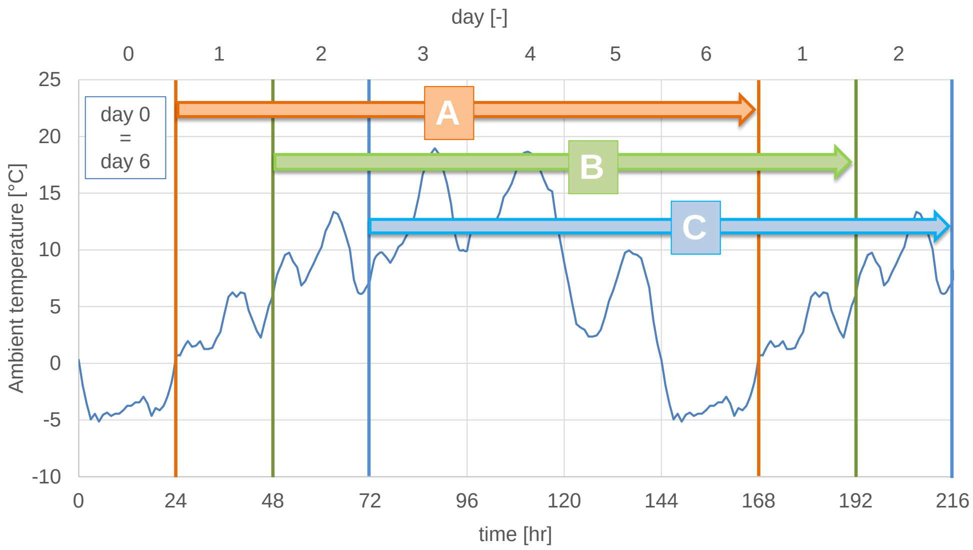



*Figure 7: Possible 6-day evaluation sequences for the test.*

Table 1 shows how well the "concise cycle" criteria was met by the three system tests. The performance factors of the recycled day deviate by less than 1 % for two of the three tests, and by 3.1 % for the third test. On the other hand, the deviation in electric energy consumption is below 1 % only for one of the three tests, and it deviates 6 – 9 % for the other two tests. This has to do with a deviation of the space heat supply of these two tests. In theory, there should not be any deviation of space heat supplied, which shows some initial problems with the implementation of the test method as already pointed out in section 2.4.

*Table 1: Evaluation of the concise cycle criteria – comparison of first and second run of days with same profile.*

| | $Q_{SH}$ | $Q_{DHW}$ | $Q_{C}$ | $W_{el}$ | $PF_{sys}$ |
|---|---|---|---|---|---|
| **System 1 for Air Source Zürich SFH100 load** | | | | | |
| Day 6 first run | -62.5 | -7.90 | 0 | 30.0 | 2.35 |
| Day 6 second run | -57.0 | -7.90 | 0 | 27.4 | 2.37 |
| Difference | -8.8 % | 0.0 % | -- | -8.7 % | **0.9 %** |
| **System 2 for ground source Zürich SFH45 load** | | | | | |
| Day 1 - first run | -50.5 | -9.62 | 6.35 | 15.3 | 3.93 |
| Day 1 - second run | -48.4 | -9.50 | 6.45 | 14.3 | 4.05 |
| Difference | -4.0 % | -1.2 % | 1.6 % | -6.4 % | **3.1 %** |
| **System 3 for air source Zürich SFH45 load** | | | | | |
| Day 6 - first run | -56.7 | -7.87 | 46.26 | 22.49 | 2.87 |
| Day 6 - second run | -56.7 | -7.90 | 45.55 | 22.41 | 2.88 |
| Difference | 0.0 % | 0.4 % | -1.5 % | -0.4 % | **0.3 %** |

*S1: Ratiotherm-SERC system, S2: Regulus-CTU System, S3: ESSA-IWT-SPF system. $Q_{SH}$ = heat delivered to space heating, $Q_{DHW}$ = heat delivered to domestic hot water, $Q_{C}$ = heat input from solar collectors, $W_{el}$ = electric energy demand of the system, $PF_{sys}$ = performance factor of the system.*

# 3 Validation of direct extrapolation

It was claimed that the results from the 6-days short test sequence may be directly extrapolated to annual figures by multiplication factor 365/6 in order to get the annual performance figures (see Eq.1) for the same boundary conditions. Further details on this approach have been given in report Deliverable 2.3:

$$X_{annualDirectExtrap} = X_{6daysTest} * 365/6 \qquad \textit{Eq.1}$$

with X variable standing for Space Heating load ($Q_{SH}$), Domestic Hot Water load ($Q_{DHW}$) or electricity consumption ($W_{el}$) of the whole system.

Following this approach, the seasonal performance factor (SPF) for the six day period equals the SPF for the whole year.

Table 2 shows a comparison between the results from direct extrapolation to annual figures, and derived from annual simulations with calibrated system models.

*Table 2: Annual results based on direct extrapolation method and based on annual simulation method (bracket)*

| | $W_{el,SHP+}$ | $SPF_{SHP+}$ |
|---|---|---|
| **System 1 for Air Source Zürich SFH100 load** | | |
| **Direct extrapolation** | a) | a) |
| **Annual simulation** | 7093 kWh | 2.43 |
| **Difference** | a) | a) |
| **System 2 for ground source Zürich SFH45 load** | | |
| **Direct extrapolation** | 2392[b)] | 4.60[b)] |
| **Annual simulation** | 2262 | 4.85 |
| **Difference** | 5.7 % | -5.2 % |
| **System 3 for air source Zürich SFH45 load[c)]** | | |
| **Direct extrapolation** | 3224 | 3.55 |
| **Annual simulation** | 2978 | 3.81 |
| **Difference** | 8.3 % | -6.8 % |

*S1: Ratiotherm-SERC system, S2: Regulus-CTU System, S3: ESSA-IWT-SPF system.*

*a) Figures not available due to problems with the compressor in the Ratiotherm system that did not work properly during the WST test. This, together with two other smaller system faults, mean that the system did not function properly and there are no valid WST measured results that can be used for direct extrapolation. The given figures (in brackets) are for annual simulation results for SFH100 building in Zurich climate with a model calibrated with the test results.*

*b) Net electricity supplied to the system, i.e. whole system electricity consumption reduced by synchronous PV production. In addition the PVT collector could deliver 1142 kWh/a to the grid.*

Unfortunately, for system S1 no comparison between direct extrapolation and annual simulation is possible because of malfunctioning of the compressor speed control. Although the system S2 (Regulus-CTU system) actually included the use of photovoltaic electricity to cover the synchronous electricity demand of the heat pump, and thus a feature for which the direct extrapolation was never validated by simulation before, the match between direct extrapolation and annual simulation is quite good (±6 %). System S3 included the use of uncovered collectors as the only source of the heat pump, which is equally a feature for which the direct extrapolation method has not been tested by simulations before. Despite this, also for this system the agreement is quite good with a maximum deviation of +8.7 % for the electricity use and a deviation of only 6.8 % for the SPF.

# 4 Additional experiences

## 4.1 Measurement uncertainties

Inside the test facilities used to characterize the performance of prototypes at CEA INES, SERC and HSR SPF, the measurement devices including sensors and acquisition chain show limited accuracy depending on temperature and time drift. This implies an uncertainty for each measured quantity for each time step. Table 3 is showing the integration of the uncertainty along the whole 6 day test.

*Table 3: Measurement uncertainties during 6-day tests*

| Measurement errors | | $\Delta Q_{SH}$ | $\Delta Q_{DHW}$ | $\Delta E_{el}$ | $\Delta Q_{c}$ | $\Delta Q_{HP}$ |
|---|---|---|---|---|---|---|
| **Ratiotherm system** | kWh | 6.0 (4.1 %) | 0.5 (1.0 %) | 0.7 (1.0 %) | 1.4 (3.0 %) | 10.1 (6.2 %) |
| **Regulus system** | kWh | 1.8 (1.4 %) | 0.5 (1.1 %) | 0.6 (1.3 %) | 0.8 (1.4 %) | - |
| **SPF-IWT system** | kWh | 1.3 (1.0 %) | 0.5 (0.9 %) | 0.2 (0.3 %) | 1.6 (1.1 %) | - |

The uncertainties for the measurements of heat transfer and electricity consumption were all in the range of ±2 %, with the exception of the space heat and collector loop energy measurements for the Ratiotherm system that were in the range of ±4 %. The resulting uncertainties for the seasonal performance factors $SPF_{SHP+}$ are 1.7 % for the measurements on the Regulus system, and 4 % for the Ratiotherm system. This higher uncertainty is a result of low flow rates in the space heating loop or small inlet-outlet temperature difference leading both to lower accuracy of the measurements.

## 4.2 The new method in comparison to the CCT at SPF HSR

The following is a summary of experiences with the harmonized test method in comparison to the previously applied CCT test method at SPF HSR:

- The method to achieve identical heat loads for space heating successfully demonstrated its applicability. This was one of the conditions for the test method to be a benchmark test.
- The direct extrapolation of the test results means a massive reduction of the effort of a system test. The reason for this is that the simulations subsequent to the physical test are no longer necessary.

## 4.3 The new method in comparison to the Combitest at SERC

The following is a summary of experiences of the implementation of the harmonized test method in comparison to the Combitest method that was previously applied at SERC.

- An advantage with the harmonized test method compared to Combitest is that it is not necessary to make a conditioning of the store to a uniform start temperature before the test starts. This avoids the need for extra connections that are not used in a real system and also saves time.
- The test does not include a DHW capacity test. To provide a key figure for DHW capacity a separate test would be required.
- Similarly system losses are very difficult, or at least very uncertain, to derive from the test data. Again, a separate test would be required in order to get more information on this point.
- The thermal mass of the building means that the indoor temperature does not vary much in practice during the heating season part of the test.
- It required a lot of effort (in SERC's test rig) to be able to verify that the DHW load was followed correctly, as it has many different discharges as well as different types of discharge. This is a “start-up” problem and has to be solved only once.
- There needs to be a good routine/procedure for setting the DHW charge temperature, and in the case of external DHW units, the set DHW supply temperature, before the test is started. Finding the correct values was achieved only after several restarts of the test.
- Due to the fact that the emulators that are used at SERC were designed for different flow rates it was impossible to fix the pressure drop of the emulators and additional pumps were required in one of the emulators (space heat) in order to get the required flow. This means that the electricity use of the pumps was not as it should be according to the test method, but the difference is judged to be relatively small.
- Due to the time step of six seconds that was the lowest time step that could be achieved in this test bench, the foreseen penalty function calculations for not meeting DHW comfort criteria after six seconds of tapping could not be implemented.

## 4.4 The new method in comparison to the SCSPT at CEA INES

While running the 6-days test following the harmonized test method, several issues occurs:

- The ISO building model that was used for the simulation and emulation of room temperatures and heat transfer from the heat distribution to the building needed to be adapted to introduce a realistic thermal inertia of the air temperature inside the model.
- Hydraulic issues: DHW charge valves were not installed in a proper way in the tested system: it was discovered through analysis of the unexpected temperature drops within the tank while operating in DHW charge mode.
- Electromagnetic compatibility issue in tested system: an unpredictable behaviour of the compressor drive while operated in automatic mode was found during the test. To avoid these issues at the time of the performance test, appropriate EMC tests and electricity safety tests should be made in suitable labs previous to performance tests.

- Time synchronization issue: various data logging devices and files: 1 for test bench and 2 from the tested controllers. Time window features activated in the real controller required to synchronize the tested controllers clock, test bench clock and TRNSYS simulation time. This point is only valid if detailed analysis of the results is necessary, but not for benchmark testing and direct extrapolation.

# 5 Conclusion

The new harmonized whole system test method was applied successfully within the MacSheep project. In particular:

- The harmonized physical boundaries were applied by all test institutes and found to be logical and consistent.
- The method to achieve identical heat loads for space heating was successfully demonstrated at least for one of the three test institutes. This is an important feature for the test method to qualify as a benchmark test.
- The six day test sequence based on Meteonorm data with a resolution of 1 hour has been used successfully, and is considered to be sufficient for most applications, in particular for solar thermal and heat pump combination.
- A harmonized DHW profile and tapping procedures were applied by all three test institutes.
- The foreseen introduction of real-time penalty calculations based on temperature differences between the measured supply and the required comfort level required data acquisition time steps of 1 second. Not all institutes were able to adapt their hardware to meet this requirement. Therefore the online penalty calculation was not performed. However, it is still believed that this feature is important and should be introduced later in order to ensure a fair treatment of different systems with different comfort capabilities.
- The direct extrapolation of the test results means a massive reduction of the effort of a system test. The reason for this is that the fitting of simulation models for the determination of annual results – although still practiced in MacSheep for the reasons explained in Del. 8.3 – can be spared in the future.
- The concise cycle approach with the criteria of near to equal results for two days with the same ID after having gone through the whole cycle of days proved to be a reliable and well-functioning approach for this kind of test.

Finally, and most importantly, the determination of a benchmark result for the performance of a system for the supply of space heating and domestic hot water was successful. In particular, the difference between the annual key performance figures determined based on direct extrapolation of the whole system test results and annual figures derived from calibrated annual simulation results were low (5-8 %), despite the fact that the systems included features (direct PV use, series collector heat use) for which the method was not previously validated.

Furthermore, whole system testing revealed many problems of system control, installation, mal-functions, and non-optimal hydraulics and temperature sensor placements. Thus, for system development as well as for performance characterization, the whole system test method shows significant advantages over any approach that is based on component testing only, while at the same time being less time consuming and more straightforward.

Work that still needs to be done in further projects are:

- Dealing with methods for the extrapolation to other heat loads
- Inclusion of methods for the consideration of time-synchronous on-site PV electricity supply to the heating system (PV heat pump or PV electric heating systems)
- Checking the influence of weather data on the determination of PV electric self-consumption
- Refining the application of penalty functions

- Defining a simple heat transfer and heat capacitance calculation model for the heat emitter simulation (radiator / floor heating) and emulation in the test bench.

Further work might also include additional test sequences for the determination of the DHW discharge volume, as well as a short test cycle for the determination of heat losses with reduced uncertainty (less turnover of energy compared to the amount of heat losses).

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