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Dynamic whole system testing of combined renewable heating systems – the current state of the art

M.Y. Haller^{a)*}, R. Haberl^{a)}, T. Persson^{b)}, C. Bales^{b)}, P. Kovacs^{c)}, D. Chèze^{d)}, P. Papillon^{d)}

^{a)} SPF Institut für Solartechnik, Hochschule für Technik (HSR), CH-8640 Rapperswil, Switzerland

^{b)} Solar Energy Research Center SERC, Höskolan Dalarna, 791 88 Falun, Sweden

^{c)} Technical Research Institute of Sweden, Box 857, 501 15 Borås, Sweden

^{d)} CEA LITEN, INES BP 332, 73377 Le Bourget du Lac, France

* Corresponding author: michel.haller@solarenergy.ch, SPF Institut für Solartechnik, Hochschule für Technik (HSR), Oberseestr. 10, CH-8640 Rapperswil Tel: +41 55 222 4836, Fax: +41 55 222 4844.

Abstract

For the evaluation of the energetic performance of combined renewable heating systems that supply space heat and domestic hot water for single family houses, dynamic behaviour, component interactions, and control of the system play a crucial role and should be included in test methods. New dynamic whole system test methods were developed based on "hardware in the loop" concepts. Three similar approaches are described and their differences are discussed. The methods were applied for testing solar thermal systems in combination with fossil fuel boilers (heating oil and natural gas), biomass boilers, and/or heat pumps. All three methods were able to show the performance of combined heating systems under transient operating conditions. The methods often detected unexpected behaviour of the tested system that cannot be detected based on steady state performance tests that are usually applied to single components. Further work will be needed to harmonize the different test methods in order to reach comparable results between the different laboratories. A harmonized approach for whole system tests may lead to new test standards and improve the accuracy of performance prediction as well as reduce the need for field tests.

Keywords: whole system testing, solar thermal, heat pump, renewable heating, dynamic testing, energy labelling, simulation, emulation, hardware in the loop

1 Introduction

With the commitment to the Kyoto protocol and the unknown future that climate change may bring upon humankind, improving efficiency and above all reducing the use of non-renewable energetic resources has become a primary objective for the development of new heating systems for buildings. Thus, comparing the energetic performance of different products that are sold on the market has become an every-day issue for policy makers, product developers and consumers. For central heating systems that provide domestic hot water and space heat, the task of determining a standard annual energetic performance is not an easy one. This applies especially if combined renewable resources are used such as solar thermal energy and heat pumps, and even more so when the heat pump uses heat from the solar collectors as a heat source. But also the energetic performance of biomass boilers combined with solar thermal heat has proven to be dependent on many details [1-5]. The steady-state performance of solar thermal collectors, of heat pumps, and of biomass boilers under different boundary conditions is usually known from test reports that are based on standards such as EN 12975-2 [6] for solar collectors, EN 14511-3 [7] for heat pumps, and EN 303-5 [8] for biomass boilers. However, when such components are built into real heating systems new questions arise that cannot easily be answered by the single component tests. These questions comprise e.g. the transient behaviour that may include the on- and off-cycling of auxiliary heaters, pumps and motors, as well as runtime and standby losses of connecting elements, of storages, and of other components. In the case of a combination of different renewable heat sources into one system and/or of serving different needs such as domestic hot water (DHW) and space heating (SH), the control of the overall system, the hydraulic solution of the system integration, and the interaction between the different components may play a crucial role in the overall system performance. From field measurement experience of

single or two family home heating systems Papillon et al. [9] showed that unwanted system interactions and high heat losses, sometimes caused by installation mistakes or mistakes in system design and control, are frequent and may affect the energetic performance of renewable heating systems quite badly. From these findings the authors deduce two recommendations for small combined renewable heating systems (single or two family house units):

1. They must be produced and sold as compact pre-fabricated units, such that the work of the installer on site can be reduced to a minimum and thus the possibility of on-site errors of installation is almost zero.
2. They must be tested as whole systems under transient, realistic, and reproducible operating conditions.

The current standard for solar combi systems, CEN/TS 12977-2 [10], has a methodology of testing single components, modelling them based on the test results and then putting the component models together into a system model in order to estimate the annual system performance. This method is generally called the CTSS (component testing and system simulation) method. On the other hand, "whole system testing" (WST) for heating systems is a different approach that has been developed over more than a decade with the following main aims:

To test complete systems with realistic boundary conditions that comprise all main operating conditions. This checks that the system works as designed in all conditions.

The results from the test can be used for extrapolation to a complete year for the nominal boundary conditions of the test (climate, building and heat distribution system).

The WST approach requires accurate emulation of the boundary conditions around the system, mainly the loads for space heating and domestic hot water, as well as the solar thermal yield, which in turn are dependent on the operation of the system. WST methods have been developed in recent years by four different institutes in Europe (Table 1). A short summary of results and experiences at the different test benches for WST methods have been presented in Papillon et al. [11].

Table 1: Names of the different WST test methods and institutes.

short name	long name	institute / country	references
CCT	Concise Cycle Test	SPF / Switzerland	[13-15]
Combitest	-	SERC & SP / Sweden	[12, 16]
SCSPT	Short Cycle System Performance Test	CEA INES / France	[17]

Bales [12] developed a method based on WST and compared it with the CTSS method. The main advantages and disadvantages of the two different approaches is summarised in Table 2.

Table 2: Advantages (+) and disadvantages (-) of two different approaches to system testing according to Bales [12].

<i>Component test and system simulation (CTSS)</i>	<i>Whole system testing (WST)</i>
(+) annual simulation can be performed for any climate or load	(+) interaction between components is tested for realistic boundary conditions
(+) ability to scale up and down in system size easily	(+) controllers can be tested for complete range of operating conditions
(+) component tests are independent of one another so if one component in a system is changed only this new component needs to be tested	(+) systems with components that are difficult to model can be tested
(-) the interaction between components is not tested	(-) benchmark results for only one climate and load
(-) limited to components that can be modelled easily	(-) system needs retesting if one component changes
(-) control algorithms are not always available from manufacturers (needed for system simulation)	(-) complex test rig required
	(+/-) model fitting and system simulation can be applied if results for other boundary conditions (climate and load) are desired

Hardware in the loop tests are common practice in electrical, especially also in automotive engineering [18,19], but it is less common in testing heat supply systems. Several authors [20-22] have used building simulation and

emulation for the development of control strategies for heating, ventilating and air conditioning (HVAC) systems. Da Silva & Knabe [23] described a dynamic test method based on building simulation and emulation that was used for the development and fault detection of boilers. Riederer et al. [24] developed a dynamic test method for geothermal heat pump systems that included simulation and emulation of the building.

The methods shown in Table 1 go beyond the testing of controllers only since they include energy storage(s), energy conversion unit(s) and the complete hydraulics of the system as far as it is usually installed in a technical room. Although they all follow the same principle idea of WST, they differ in many ways and details, including the definition of the physical boundary around the tested systems where the energy flows going in and out of the system are measured.

Within the project "MacSheep", funded from the European Union's Seventh Framework Programme, the different institutes currently merge their experiences in WST and work towards a new harmonized test procedure. The main goal of this harmonization is to be able to compare results from the different tests carried out at the different institutes. At the same time, the complexity of these test methods shall be reduced where it can be reduced without losing important capabilities or accuracies.

The main aim of this study is to describe and compare the different versions of whole system testing that have been applied at the four test institutes and to analyse their advantages and disadvantages. The study leads to suggestions for future work that is necessary in order to further develop these methods and to harmonise the approach towards a single test method. The base for this study is the experience gained from applying WST methods over more than 12 years and on more than 35 heating systems. For illustration, example results from one whole system test on a solar and heat pump system are presented. Additionally, examples are given of how the approach can discover substantial deviations between the real behaviour of a system and the behaviour that was expected by the designer.

2 Description of Test Methods

2.1 Aim of the test methods

WST methods shall show the transient behaviour and energy consumption of a complete heating system under real-life conditions for different days of the year. The loads that have to be covered for domestic hot water (DHW) and space heating (SH) should be as much as possible identical for all tested systems, such that the test results can be used for benchmarking purposes, and to either directly extrapolate to annual energetic performance or to obtain the annual energetic performance by means of parameter identification and simulation. The core test sequence should meet the following requirements:

It is composed of a number of consecutive test-days, each one representing a real day of the year.

The test is 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 (fuel and/or electricity) needed to cover the demand. In the case of solar and heat pump system, the only auxiliary energy consumption is the electric energy demand. The following figures of merit, either taken directly from the core test sequence or from the extrapolation to annual values, can be shown based on the test results:

Total electricity and fuel consumption during the test sequence / whole year.

Ratio of useful heat output divided by total consumption of purchased energy (performance factor).

Fractional energy savings (fsav) compared to a reference system without solar thermal energy that is defined once and for all for a system with the same auxiliary heating principle (fuel oil, natural gas, biomass boiler or heat pump).

2.2 The physical boundary of the tested system

The tested system includes all or most of the components of a combined renewable heating system that are usually located within the so-called technical room. In the case of air-source heat pumps, the air-source heat exchanger unit, that may also include the evaporator or the whole heat pump as a monobloc unit, is placed in a climatic chamber. The interface of the test rig with the tested system is defined by the points of measurement of the energy balance between the test rig and the tested system. The boundary of the tested system for the three

different WST methods is shown in Figure 1 for the example of an air-source heat pump system. Heat losses that occur within the boundary shown in Figure 1 are regarded as non-useful, with the exception of stoves that are intended for installation in the occupancy area of the house.

The tested system comprises the following components within its boundaries:

The storage tank(s).

The solar group (pumps, valves controller).

The auxiliary heating unit(s) (a heat pump, boiler or stove and possibly electric backup heating elements).

Any additional devices needed to provide DHW (e.g. external heat exchanger and pump, passive mixing device for scalding protection if needed).

Most notably, the solar collector field itself is never part of the tested system. The reason for this is that the physical installation of this part would result in the need to have reproducible conditions for the collector field in terms of ambient temperatures and irradiation. Although solar simulators could be used for this purpose, it is rather impractical to put a 10 – 30 m² solar collector field under a solar simulator and then run a consecutive test sequence of several days in order to study the system performance. The solar collector field is therefore simulated and emulated during the test. For this purpose, the performance characteristics of the solar collectors must be known prior to the system test, e.g. from a Solar Keymark test according to EN 12975.

Figure 1: Simplified hydraulic scheme showing the system boundaries where the energy balances are measured at the three different institutes for the example of an air source heat pump and solar system.

Differences between the physical boundaries of the systems tested at the different institutes are:

In the Combitest method the actuator of the space heating temperature control mixer is controlled by the test rig instead of the tested system in order to achieve a fix heat load.

The connecting tubes between the space heat distribution pump / mixer group and specified points at the test-room walls are only included for CCT, but not for SCSPT or Combitest.

Connecting tubes of 15 m length between the solar group and the solar collector field are only installed for CCT, but not for SCSPT or Combitest.

The CCT test method includes an un-insulated 2.5 m DHW distribution pipe with defined inclination in order to disadvantage systems that are supplied without heat traps.

To properly evaluate the Combitest method an energy meter is required between the auxiliary heater and the store as well as hydraulic connections to the top and to the bottom of the store and also of the boiler for conditioning to defined temperatures and measure the charge status of the store and the boiler before and after the test sequence.

2.3 General principles and procedures

Common features for all three WST methods are:

The tested system and its controller(s) are set up the same way they would be set up in a field installation and then left to operate uninterruptedly for the whole duration of the test sequence. An exception is the actuator of the space heat mixing valve for Combitest as mentioned above.

The core test sequence is lasting several days (6 for Combitest, 12 for CCT or SCSPT), where each day corresponds to a real day of a meteorological year. There may be additional pre-conditioning time at the beginning or additional "post-check" days added at the end to assure that the state of energy of the system at the beginning of the core-test sequence does not deviate significantly from the state at the end of the test sequence. Thus, measurement of the change in internal energy of the storage or other parts of the system can be avoided.

During the test sequence, the collector yield is simulated and emulated, thus taking into account the response of the tested system at all times (in particular the return temperature to the collector field and the mass flow). For the solar pump control, the system controller needs to know the outlet temperature of the emulated collector. This is achieved by either emulating the collector temperature sensor, by placing the sensor in the emulator for the collector or by placing the sensor in a separate emulator for the collector temperature.

The response of the heat distribution system is simulated and emulated (CCT and SCSPT) or based on a load-file (Combitest). For the CCT and SCSPT method, the controller of the system often requires information about the ambient outdoor temperature in order to calculate the flow temperature set point of the heating system. For this purpose, the ambient outdoor temperature sensor is either emulated or placed in an emulator for the outdoor temperature.

Domestic hot water load profiles are applied as realistically as possible in CCT and SCSPT with frequent and possibly also short tappings according to a fixed tapping schedule. This tapping schedule can foresee that a certain amount of energy must be tapped at a certain time, thereby counting the energy only after the hot water temperature has reached a certain temperature level that is considered to be the "useful" temperature. In contrast to these two methods, the Combitest method includes six larger draw offs per day and all energy discharged is counted.

The procedure for simulation and emulation can be described as follows:

At the end of each time step, measured values are passed from the test bench control software to the system simulation software.

Based on these values, the simulation software is simulating the answer of the emulated device for the next time step and returns the result to the test bench control software.

During the next time step, the test bench control software controls the emulation of the simulated device, while the simulation software pauses and waits for the next input of measured values from the test bench control software.

Alternatively, emulation can also be based on load files that do not depend on the behaviour of the tested system, thereby loosing part of the true response of the emulated device. Table 3 shows similarities and differences of the general software solutions, simulation time steps, and test durations of the three different WST methods.

Table 3: General information about the test sequence and the software used for simulation and emulation.

Feature	CCT	Combitest	SCSPT
Test bench control software / system simulation software	LabVIEW / TRNSYS16	LabVIEW / TRNSYS16	LabVIEW / TRNSYS16
Time step of simulation/emulation	1/32 h	0.005 h	1/60 h
Duration of core test sequence	12 days	6 days	12 days
Pre-conditioning ^{a)}	18 hours	2 days	12 hours
Status of storage before pre-conditioning	lower part: 20-30 °C, DHW charged	20 °C	20 °C
Post-check time ^{b)}	0	0	2 days

a) Pre-conditioning is a number of days or hours with the same climate and conditions as on the last day / hours of the core test sequence that shall assure that the states of energy of the system (e.g. storage) at the beginning and at the end of the core test sequence do not differ substantially from each other.

b) Post-check time is a number of days or hours with the same climate and conditions as on the first days or hours of the core test sequence that will show the same system performance as these if the state of energy of the system at the beginning and at the end of the core test sequence do not differ substantially from each other.

Care has to be taken when a simulation software is used that uses constants for the specific heat of water (and other fluids), such as is the case for TRNSYS [25]. Since these values are not constant in the test bench, the information exchange between the test bench control software and the simulation software must not be based on volume flow rate and supply and return temperatures, but rather mass flow rate, transferred power and one temperature.

Once the simulation results are known to the test bench control software, the control of the emulation during the following time step can be based on:

Constant return temperature from the test bench to the tested system based on the simulation results. It has to be noted that for Combitest also the space heating supply temperature is controlled by the test bench.

Constant heating or cooling power from the test bench to the tested system based on the simulation results.

Two kinds of sources for inaccuracy can be monitored and corrected for during the test:

1. The **test bench** behaviour is **not ideal**, leading to a deviation between a power set point and the achieved power during an emulation time step. This may or may not be compensated for in the following time steps
2. The input data for the simulation was based on measurements acquired before the emulated time step (**ex-ante simulation**), and this data **may deviate from** the measurements during the current time step. The influence of this deviation can be detected by carrying out an **ex-post simulation** after the end of the emulation time step that uses the exact measured values of this time step. The power difference between ex-ante and ex-post calculation can be compensated for by correcting the set point(s) of the following time step(s).

2.4 Climate

The climates used as a base for the test procedures are all based on the climate of Zurich (Table 4). This is due to the fact that the development of these test procedures were initiated while the different institutes worked together in the IEA SHC Task(s) 26 and 33, where the climate of Zurich was used as a reference climate for the common work that was carried out.

Based on the annual climate data, different procedures have been used to select single days for the composition of the test sequence. For the CCT, the criteria for selecting the different days were the representativeness of the whole cycle's temperature and irradiation average for the whole climatic year, as well as representativeness of each day for the temperature and irradiation average of the corresponding month. For Combitest, the selection has been done such that the six day period simulation would give the same fractional energy savings as an annual simulation as well as the same conditions in the storage at the start and end of the core test sequence [12]. This was made for a range of system types and sizes. For the SCSPT an automated optimization approach was used that iteratively selected 12 days from the year and simulated a solar combi system with this 12-days climatic profile. The target function was the combination of absolute differences between the 12-day test sequence results multiplied by 365/12 and the annual results for backup (natural gas) energy consumption, space heating demand, and domestic hot water demand. The resulting test sequence has shown deviations below 3% with regard to

backup energy consumption for a number of different test cases: collector areas 8-20 m², storage sizes 400 – 1000 liters. Moreover, a pre-selection for the possible choices for the twelve days was applied to ensure that the evolution of daily averaged ambient temperatures and irradiation over the twelve selected test days matched the evolution of these values over the whole year (visual check, soft criteria) [26,17].

Table 4: The different annual climatic data used as a base for the test procedure.

Feature	CCT	Combiteest	SCSPT
Location	Zürich, Switzerland	Zürich, Switzerland	Zürich, Switzerland
Climate data origin	Measured values, TRY ^{a)}	Meteonorm	TRY provided by Meteonorm
Time step of the data-source (min)	10	60	60
Annual temperature average (°C)	9.0	9.1	9.07
Annual irradiation total on the horizontal (kWh/m ²)	1111	1088	1087
Annual wind speed average (m/s)	1.2	2.2	2.2
Annual moisture average (% rH)	76.4	76.6	75.3

^{a)}Test Reference Year assembled at the SPF specifically for the CCT method.

2.5 Building load emulation

The different approaches in Building load simulation and emulation are shown in Table 5.

Table 5: Data on the building load simulation and emulation for the three test methods.

Feature	CCT	Combiteest	SCSPT
Basic annual heat load	12 500 kWh/a 100 kWh/(m ² a)	13 300 kWh/a	8480 kWh/a 60 kWh/(m ² a)
Base for heat load emulation	Real time simulation	Fixed load file	Real time simulation
Test-bench set point	Temperature	Temperature	Temperature
Compensation for non-ideal test bench behaviour	NO	YES for SERC, NO for SP	NO
Ex post simulation	used for room temperature only	NO	NO
Flow temperature to heat distribution system	Controlled by tested system	Controlled by load file / test bench hardware	Controlled by tested system
Emulation of thermostatic valves	YES, based on real time simulation	NO, mass flow constant 300 kg/h	NO, mass flow constant 600 kg/h
Emulated outdoor temperature feedback to controller	YES	NO	YES
Emulated indoor temperature feedback to controller	NO	NO	YES
If thermostatic valve: Minimum mass flow rate guaranteed?	YES	NO	-
Heat load during physical test dependent on tested system	YES	NO	YES

2.6 Hot water draw-off

The following devices are considered to be part of the tested system:

Scalding protection (usually a passive tempering valve set to 52.5 °C) for systems without external heat exchangers.

Any heat exchangers, pumps and controllers needed (e.g. for external DHW preparation).

The hot water draw off may be linked to the simulation time step or not. If it is not linked, it may be based on a table with start-times and energies to be tapped for each draw off. The stop time may thus not be at a fixed time of the test-procedure, but after the energy target has been reached (see Table 6).

Table 6: DHW profiles used in the test (do not need to be identical with annual DHW profile).

Feature	CCT	Combitest	SCSPT
Origin of the draw-off profile	[27]	[12]	[27], IEA SHC Task 26
Draw offs smaller than a simulation time step included	YES	NO	NO
Energy type draw offs	YES	YES	NO
Volume type draw offs	YES	NO	YES
Variable flow rates	YES	YES	YES
Useful temperature	variable: none, 30 °C, 38 °C, 40 °C	40 °C	45 °C
time limit for reaching the useful temperature	40 sec	NO	NO
time limit for reaching the energy set point	variable (dependent on amount drawn)	NO	NO
Cold water temperature	variable, 8.5 – 19.0 °C	10 °C	variable, 6 - 14 °C
Draw offs per day	variable	6	variable
Total draw off energy	100 kWh / 12 days	48 kWh / 6 days	100 kWh / 12 days

Additional tests can be carried out to gain additional information. E.g., the system performance for a specific combi system is affected by the auxiliary set temperatures and auxiliary volume, which also influence the hot water capacity, meaning that lowering the hot water capacity will increase solar fraction. Therefore an additional test procedure after the core test period is applied for Combitest in order to quantify the minimum hot water capacity. In this procedure, the storage is discharged with the space heating circuit until the auxiliary heater starts. At that time a DHW discharge of 0.3 l/s at 40°C with 10°C cold water temperature is performed until the DHW-temperature drops below 40°C. Finally the storage is conditioned to 20°C.

2.7 Solar collector field simulation and emulation

The collector simulation and emulation during the test is based on collector performance test data according to EN12975-2 from a certified testing institute that must be available before the test start and includes the following figures:

Reference area (m^2) of one collector element (usually the aperture area).

Zero loss efficiency (-), linear heat loss coefficient ($W/(mK)$) and quadratic heat loss coefficient ($W/(m^2K^2)$)

Specific heat capacitance of the collector ($J/(m^2K)$)

Incident angle modifiers for different incidence angles, bi-directional for vacuum tube collectors

pressure drop (Pa) of one collector element

mass flow rate (kg/h) at which the collector has been tested and at which the pressure drop has been evaluated

The collector simulation models used are compatible with EN 12975-2, including incident angle modifiers as well as thermal capacity. For collectors that are operated below the ambient temperature, condensation gains or effects of frosting may have to be considered in the simulation. Uncovered collectors may need additional data according to EN 12975-2. The differences in solar collector field simulation and emulation are shown in Table 7.

Table 7: Collector field simulation and emulation.

Feature	CCT	Combiteest	SCSPT
Simulation model	TRNSYS Type301 [28]	TRNSYS Type832 [29]	TRNSYS Type832 [29]
Slope and orientation	45° south	45° South	45° South
Collector parameters	Based on individual test report	Based on individual test report	Fixed reference parameters or based on individual test report
Max. collector field area	15 m ²	15-20 m ²	30 m ² (25 kW) with 16 m ² as usual value
Set point for emulation	Power	Temperature	Temperature
Compensation for non-ideal test bench control	YES	YES	NO
Compensation with ex-post simulation	YES	NO	NO
Fluid in the collector loop	Water glycol mixture	water	water
Collector temperature sensor of the tested systems' controller	Placed in a collector temperature emulator	Placed in the emulation loop	Placed in the emulation loop or emulated with a resistance box
Collector loop pipes included in tested system	2x15m ² installed / part of tested system	NO	NO

2.8 Extension of the test methods

The Combiteest and CCT methods were also extended to measurements of flue gas emissions such as CO, NO_x, TOC and PM2.5 [30,31]. If total emissions shall be calculated in terms of mg emission per MJ heat supplied, this includes reliable and accurate continuous measurements of flue gas flow rate [32].

2.9 Test evaluation and post processing

During the core test sequence, the domestic hot water temperature limits set for the different draw offs have to be reached. The simulated room temperatures (CCT and SCSPT) have to fulfil certain requirements such as never dropping below 19.5 °C. No simulation of room temperatures is performed in the Combiteest method.

The direct graphical evaluation (curve plots of measured temperatures, mass flow rates and power) are interpreted directly after the test and give in-depth information about the system's behaviour. Based on the measurement of energy input and output at the tested system's boundaries, the total electricity demand, fuel consumption, delivered space heating energy, and delivered DHW energy are calculated.

For the Combiteest method, energy balances are checked and the data are compensated for mismatch in space heating load and mismatch in the energy stored in the storage tank [16, 33]. For the CCT method the difference of energy stored in the storage between the beginning and the end of the core test sequence is entering the evaluation procedure described below.

The Combiteest and SCSPT use direct extrapolation from the measured test results to annual energy consumption (multiplication of the test results with 365/6 or 365/12 respectively). Combiteest extrapolations include a correction factor derived by Bales [12] that was derived from a correlation between results for the test sequence and results for annual simulations for a number of system types and sizes. The procedure for the CCT method is not based on direct extrapolation, but on fitting and simulation:

1. A model for the tested system is created with all the known parameters from manufacturer's documentation and additional tests for the heat loss of the storage and – if needed - also for the efficiency of the auxiliary heating device.

2. Missing parameters and uncertain parameters of the model are fitted to the test results by re-simulating the test-days and comparing the results with the measured values.
3. A whole year is simulated with the fitted model. In the annual simulation, the heat load is defined by a load-file (not dependent on the tested system). The DHW load that is read in from a load file is multiplied by the factor $fr_{DHW} = \dot{Q}_{ms,tot} / \dot{Q}_{ms,useful}$, where $\dot{Q}_{ms,useful}$ is the measured DHW energy tapped during the test at times where the DHW supply temperature was above the “useful” temperature limit, and $\dot{Q}_{ms,tot}$ is the total energy tapped that includes also energy that was tapped with DHW supply temperatures below the “useful” temperature limit.

Extrapolation to other climates and heat loads is possible with the CCT method using annual simulations where the climate and the heat load are replaced with other climatic data and heat load data. For the SCSPT, an extrapolation procedure is currently developed at CEA INES [34–36]: The measured data are used to identify a dynamic simplified model of the whole system. The simplified model called “grey box model” combines simplified physical equations (collectors, building, storage, auxiliary = “white box”) and an artificial neural network (“black box”). Once the simplified model is selected and validated, it can be used for various boundary conditions (collector area, building and climate) in order to obtain annual results. However, for all extrapolation methods the more the climate and loads deviate, in particular the more the temperatures required for the heat distribution system deviate from the tested temperatures, the more the uncertainty of the extrapolation is expected to increase.

3 Test results

3.1 Results from a combined solar and ground source heat pump system

In Dec. 2012, a ground source solar and heat pump system was tested at CEA INES / France. The system was of the parallel solar and heat pump type as shown by the energy flow chart that was developed within the IEA SHC / HPP Task 44 / Annex 38 (T44A38) [37] in Figure 2.

Figure 2: The T44A38 energy flow chart of the tested ground source solar and heat pump system.

The results of the system test are shown in Table 8 and Figure 3. The system's performance factor on single days ranges from 3.0 in winter to 21.3 in summer, where the heat pump did not have to deliver any heat to the storage or to the space heating. The overall performance factor of the system was 4.2. From the results it can be seen that the heat delivered by the heat pump in DHW mode correlates more with the space heating demand than with the DHW demand, and that it is in winter several times higher than the space heating demand. This is a strong indication that there is potential for improvement concerning the hydraulics and control of heat pump integration

into this system. Reasons for this may be that there is only one return line from the storage to the heat pump that is used for both, DHW mode and space heating mode of the heat pump, and that unexpected mixing occurs in the storage tank.

Table 8: Results of the 12-days measurements performed on the ground source system.

Day	$T_{amb,av}$	I_{hor}	Q_{SH}	Q_{DHW}	$Q_{HP,SH}$	$Q_{HP,DHW}$	Q_C	W_{el}	N_{starts}	PF_{sys}
-	°C	kWh/m ²	kWh	kWh	kWh	kWh	kWh	kWh	-	-
1	1.6	1.000	-62.1	-13.1	12.5	57.6	4.2	23.3	11.0	3.23
2	1.9	1.751	-55.0	-6.2	12.2	47.7	7.5	19.7	9	3.10
3	6.3	2.173	-39.1	-6.6	14.0	21.9	22.2	9.6	4	4.77
4	8.1	4.188	-31.7	-8.2	2.6	15.0	25.8	7.0	2	5.70
5	17.6	5.360	-15.1	-5.3	9.8	7.2	35.9	3.8	1	5.36
6	18.8	5.084	-12.2	-11.7	8.0	0.0	32.6	1.2	0	20.77
7	18.0	4.296	-12.2	-7.8	1.2	-0.1	31.9	1.1	0	17.60
8	14.4	3.714	-13.5	-5.5	-0.4	0.0	27.0	1.0	0	19.28
9	8.7	3.091	-9.3	-10.1	-0.3	-0.1	11.4	0.9	0	21.29
10	1.9	1.751	-35.3	-8.0	7.7	26.9	7.7	10.6	4	4.10
11	2.1	1.009	-47.2	-10.8	12.9	42.3	7.1	17.6	7	3.29
12	1.3	0.575	-56.3	-8.1	19.7	50.8	0.0	21.5	10	3.00
Tot	8.4	33.992	-389.0	-101.4	100.0	269.1	213.2	117.2	48	4.18

$T_{amb,av}$ = average ambient (outdoor) temperature; I_{hor} = global horizontal irradiation; Q_{SH} = space heat energy; Q_{DHW} = domestic hot water energy; $Q_{HP,SH}$ = heat delivered by the heat pump in space heating mode; $Q_{HP,DHW}$ = heat delivered by the heat pump in DHW mode; Q_C = Collector field heat input; W_{el} = electric demand; N_{starts} = number of heat pump starts; PF_{sys} = performance factor of the whole system over one day / 12 days.

Figure 3: Results of the 12-days measurements performed on the ground source system. Abbreviations see Table 8, + Q_{evap} = heat from the ground.

3.2 Examples of unexpected system behaviour

The described test method approach has been applied for many years at the different test institutes, with more than 35 tested systems in total. Quite frequently this kind of test revealed unexpected system behaviour that

cannot be detected by testing single components and that might even go undetected in field installations if the system still fulfils the customers demand for comfort. However, the unexpected behaviour in many cases lead to inefficient systems with substantially increased demand of non-renewable primary energy or to early component failure due to the temperature limits of a component being exceeded or due to frequent on/off cycling of motors. Some of these behaviours that have been detected over the past years at the different institutes are:

- Modulating pellet boilers that fail to modulate due to the hydraulic integration into the system that prevents modulation even when the heat load is low (compare [4, pp. 91-98]). This is illustrated with Figure 4 where the “modulating” boiler runs on 12 kW heating power (the nominal value) although the heat load is 5 kW (time 0 – 6h). Part load efficiency of this boiler would be higher than full load efficiency, and less cycling would be better for the lifetime.

A system that continues to provide space heat by the gas burner at a temperature level of 25-30 °C although the combi store is charged to more than 60 °C from top to bottom.

A system where the heat pump is charging the storage for domestic hot water (45 - 50 °C), but part of this heat is subsequently used for space heating (35 – 40 °C). This is illustrated in Figure 5, where the heat pump is not only charging the DHW section of the storage (T. St. DHW), but also the space heating section (T. St. SH) while running in DHW mode. Subsequently, space heat is provided from the storage for some time by discharging the SH zone of the storage while the heat pump is turned off.

- Too frequent burner cycling: up to 897 in twelve days for an oil burner, and more than 1 000 for a gas burner unit (extrapolated around 30 000 per year).
- Annual boiler efficiencies 10-20% lower than what is given by steady state tests according to EN 303-5 [33].
- Buoyancy driven circulation between the storage and the auxiliary heating device at standby that is leading to increased heat losses.
- A system where the solar control setting for the temperature difference between the collector and the storage that is the limit for switching off the solar pump is higher than the uncertainty of the temperature difference measurement (in this case 2 K) and leads to continuation of the solar loop flow after the sun is gone and thus heat is pumped backwards to the solar collector emulator.
- Excessive mixing in the storage tank due to high mass flow rates of an auxiliary boiler or of a heat pump that delivers heat to the space heat section of the tank.

A system that was unable to keep the indoor temperature of the building around the 20°C set point particularly during the emulated heating season (see day 1-5, 9-12 in Figure 6, left) where due to solar passive gains less auxiliary heating energy would have been needed with a better control (Figure 6, right).

Figure 4: Excerpt from whole system test measurements at HSR SPF that show a pellet boiler (12 kW, 30-100%) that fails to reduce its heating power to match the space heating power of around 5 kW (hours 0 to 8).

Figure 5: Excerpts from whole system test measurements at CEA INES showing a system where a heat pump is charging the storage for domestic hot water (DHW), but part of this heat is subsequently used for space heating (SH).

Figure 6: Excerpts from whole system test measurements at CEA INES showing a system that was not able to keep the room temperatures at 20 °C (left) compared with improved system (right).

4 Discussion and Conclusion

Three similar, but yet different, WST methods for systems that provide space heat and domestic hot water for single or two family homes have been described. All of these methods have been applied successfully for testing solar thermal combi systems in combination with different auxiliary heating devices such as fossil fuel boilers (heating oil and natural gas), biomass boilers (automatically operated), pellet stoves (extended room heaters) and different kinds of heat pumps. All of them are able to show the performance of these systems under transient operating conditions that are a lot closer to the real life application than the general steady state performance tests that are usually applied to single components. However, some of the differences between the test methods may have a large influence on the test results and should be harmonized if the results of the different test methods shall be compared. Some of these differences are:

The time step of the climatic data used: Different climate data-sets are used and different days have been chosen for the core test sequence. Only one test institute uses a higher resolution of solar irradiation data obtained from measurements. It has been argued that this is necessary in order to be able to show the difference that may arise from the short term response of a system when solar irradiation increases or decreases rapidly with time (e.g. when clouds pass). Vijayakumar et al. [38] indicate that a high time resolution for the solar irradiation may be important with effects of up to 50% difference in collector yield based on simple utilizability studies, whereas

other studies that were based on collector yield simulations found only little difference ($< 1\%$ reported by Baoxin [39], $< 4\%$ reported by Furbo and Shah, [40]). Additional studies are needed, especially for solar and heat pump systems that include stratifying collector loop hydraulics and control, in order to bring more light into this controversial issue.

Different building models with different standard heat loads are currently used. Here, the ISO building model described in EN ISO 13790 [41] may simplify the procedure and ease the spreading of this kind of test method. However, for the simulation of the heat distribution system no validated international standard that is easy to implement has been found for hydronic heating radiators or floor heating slabs. More work is needed in order to find a suitable model that can be used for these tests and that can be communicated easily. Together with the model for the space heat distribution, the question arises whether thermostatic valves shall be assumed for the space heat distribution, how the exact behaviour of these valves is simulated and emulated, and whether a minimum flow through the space heat distribution shall always be guaranteed.

One method uses a fixed heat load (file) for space heating, whereas the other methods use a variable heat load that depends on the behaviour of the tested system, above all on the controller of the tested system. Whereas the first method has the advantage of leading to an equal heat load for different systems tested and thus enables direct comparison of the results, the disadvantage is that the real system's behaviour concerning space heat distribution control cannot be tested and special treatment e.g. for DHW priority of a controller is needed. Space heating distribution control may influence the performance of a system significantly and therefore it is logical that this is also part of the test. If possible, the two approaches of equal amount of space heating demand during the test while at the same time letting the controller of the system decide freely how and when to supply heat to the space heat distribution should be combined into one method.

One method uses an ex-post simulation and compensates for the deviation between ex-ante and ex-post simulation in subsequent emulation time steps. It can be argued that this is not needed if the time step for simulation and emulation is small enough. More data is needed to quantify the influence of ex-post simulation correction and to derive a recommendation when this feature should be used.

One method uses a DHW mixing valve within the test bench (outside the tested system's boundaries) in order to reduce the mass flow through the tested system when the water temperature is higher than needed, thus emulating the behaviour of a user that will change the position of the usually installed mixer at the tap and thus increase the cold water flow and decrease the hot water flow if the (unmixed) hot water temperature is higher than desired.

Two methods use 12 days for the core test sequence, whereas one method only uses 6 days. The question arises how many days are sufficient in order to get to a reliable result.

One method uses parameter fitting and system simulation to obtain annual results from the test, whereas the other two use direct extrapolation approaches. The effort for parameter fitting and simulation is certainly substantially higher than for direct extrapolation and in order to be able to do parameter fitting suitable models for the components have to be available. At the same time valuable insight can be gained into the reasons for good or bad performance and a simulation model for the tested system opens up the possibilities for studying the effect of system improvements. The question arises if direct extrapolation can be as accurate as fitting and simulation on one hand, and if the additional insight into the system is needed or even wanted if benchmark testing is the main focus on the other hand. Parameter fitting also opens up the possibility to simulate annual performance for other heat loads and climates. Additional methods have been proposed for the direct extrapolation methods to reach the same goal [36]. In both cases, this kind of extrapolation will always remain valid only as long as the general boundary conditions (e.g. the temperature of the space heat supply and return in the case of heat pumps or condensing gas boilers) do not change too much, unless a detailed model for the response of these units to these changes is included.

Harmonizing the test methods to one unified method that is applicable to most types of heating systems could make this kind of test more relevant and meaningful for companies that develop and commercialise these systems. Furthermore the generic test approach described in this article could potentially result in a European test standard that would present an alternative to the current so called component testing and system simulation method (CTSS) described in the EN 12977. In this case, the harmonization of the three different methods described here would need to be taken one step further in order to arrive at one single test procedure.

5 List of Abbreviations

CCT	Concise Cycle Test
CTSS	Component Testing System Simulation
WST	Whole System Testing
DHW	Domestic hot water
SH	Space heat
SCSPT	Short Cycle Sytem Performance Test
IEA SHC	International Energy Agency's Solar and Heating Programme
TRY	Test Reference Year
TOC	Total Organic Carbon
PM2.5	Particulate Matter < 2.5 µm
NO	Nitrogen oxides
CO	Carbon monoxide
HPP	Heat Pump Programme (of the IEA)

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