Combitest – Initial Development of the AC/DC Test Method

A Report of IEA SHC - Task 26

Solar Combisystems

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Contents

1 Introduction

Combitest is the name given to a thermal store test procedure that was the predecessor of the system test method called the AC/DC method (Annual Calculation and/or Direct Characterisation). This report can therefore be looked at in the historical context of the development of the final system test method for solar combisystems. It is essentially an extract from the authors Licentiate thesis [1], but with a more detailed uncertainty analysis and the addition of an extra performance indicator.

Combitest was developed during 1999-2000 as a new short-term test method for testing the thermal performance of water based buffer stores. It is based on knowledge gained from another short-term method, also developed at SERC, the six-day test [2] as well as from other methods such as the Component Test and System Simulation (CTSS) method [3] and the STF method [4]. Combitest has two parts:

1. Direct Characterisation (DC), where performance indicators can be derived directly from measurements.
2. Annual Calculation (AC), with parameter identification and long-term system simulations. This part is not obligatory and can be performed if the manufacturer so desires and if the system can be simulated accurately.

The development of the test method was performed entirely using synthetic test data. In this case the synthetic test (measurement) data is a file that has been produced by a simulation model. This file contains the same type of data as would a file from a real test: the input and output temperatures to the store connections and the relevant flows. This synthetic data is then used instead of real data to evaluate the test, both for direct characterisation and for simulations based on parameter identification for the exact same simulation model. The parameter values used in the model were derived using the store test of the CTSS method prEN 12977-3 [5], referred to in this report as the CEN method. These models were also put into a system model such that annual simulations could be performed for the Zurich climate and the SFH100 house, the equivalent boundary conditions for Combitest. The annual simulations were then used to compare with results for Combitest. Likewise, results for the parameter identification process using synthetic Combitest data were compared to those from the CEN method. More details of the application of the CEN method and the results obtained from it can be found in [1].

The use of synthetic data is the first stage in the development of a new test method. It gives somewhat idealised results, as the synthetic data has no noise due to sensor uncertainties. In addition, for the AC part with parameter identification, the simulation model for which parameters are identified is exactly the same as that which produced the synthetic test data, again an idealisation. If it is difficult to identify parameter values in these circumstances, then it will be more difficult with real data that includes more uncertainties. Real measurements were not performed due to lack of time within the project.

This report describes the test method called Combitest, as far as it has been developed. Firstly an introduction is given describing the initial ideas behind the test sequences and the method in general, followed by specifications for the method based on these initial ideas. The test sequences and evaluation are then described followed by the method used and the consequent results. In addition a detailed uncertainty analysis is described. Finally there is a discussion of the results and method, as well as suggestions for further work.

Combitest differs from the AC/DC system test method in that it restricts the definition of the system to include only the store subsystem including:

- Thermal store(s)
- Necessary heat exchangers for heat transfer to/from the store
- Integrated auxiliary heaters

In comparison to the AC/DC method it has standard components for the following:

- Collector type and size
- External boiler and controller, although two different types of boiler were simulated amongst the 10 variations
- Heating system and controller
- Collector controller

1.1 General

The following were the general guidelines drawn up at the start of the development of the method:

- Realistic sequences for all seasons.
- The test is split into three parts for the three different season types, but coupled together to form one whole sequence of six days.
- The store is driven into a range of operating conditions.
- Collector, boiler and loads emulated by the test stand.
- If different heaters are used for different seasons, then during the test the appropriate heater will be used for the different seasons in the test.
- The start and end conditions in the store should be as similar to one another as possible in order to minimise the need for corrections in the calculation of performance indicators.
- The sequence is to be split into three sections:
    - conditioning (to get the store into nearly the same state as at the end of the core phase),
    - core phase for which the performance indicators are calculated, and
    - final discharge in order to estimate the energy contents of the store.
- The initial core phase sequence is to be derived such that the mean values for each “season” for the important input variables are similar to the mean values for the season in a whole year.
- Analysis of the performance indicators for the test sequence should indicate how to change the sequence to get indicators that are more representative of yearly values.

1.2 Climate Data

- The days were chosen according to the rough guide for the different parts (seasons) of the test.
- The average for each part should be close to the average for the relevant season.

1.2.1 Winter (November - February)

General conditions:

- little or no solar radiation,
- space heating required all day,
- winter auxiliary heater used, and
- priority for matching to seasonal averages: heating load, total solar, direct/diffuse radiation ratio.

Functions addressed by the test:

- storage capacity of store during discharge,
- time in between charges, i.e. a measure of the thermal storage capacity of the auxiliary heated part of the store,
- how the store interacts with the boiler under high load, and
- whether the store can utilise a little solar radiation during winter.

1.2.2 Spring/Autumn (March, April, September, October)

General conditions:

- variable solar radiation,
- space heating required all day or part of the day,
- winter auxiliary heater used, and
- priority for matching to seasonal averages: total solar, heating load, direct/diffuse radiation ratio.

Functions addressed by the test:

- how the store can utilise available solar under varying conditions with space heating varying widely and average DHW loads.

1.2.3 Summer (May-August)

General conditions:

- no space heating,
- summer auxiliary used, and
- priority for matching to seasonal averages: total solar, ambient temperature, direct/diffuse radiation ratio.

Functions addressed by the test:

- heat loss at high temperatures and fully charged tank, and
- heat capacity of store as charged by solar.

1.3 Heating and Domestic Hot Water Loads

- Domestic Hot Water. An average daily load of 200 litres, with constant inlet temperature of 10°C and outlet temperature of 45°C.
- Space heating load taken from simulations of a house with 100 kWh/m^2.year heating requirement in Zurich. The heating load data is for the same time as the weather data. This was a preliminary version of the SFH100 house defined for the work of IEA SH&CP Task26.

2 Specifications

2.1 Aims

The aims of the Combitest method are as follows

- It can be operated at two levels:
  - A simple level, called Direct Characterisation (DC), based solely on measurements. Results are in the form of performance indicators that are derived from input-output relations. The overall functioning of the store is also assessed.
  - A more detailed version, called Annual Calculation, using parameter identification and long-term simulations, as with the full CEN method. Extra test sequences might be required to get good parameter identification results.
- It is suitable for all types of water based thermal buffer stores used for single family houses (volume range: 0.3 – 2.0 m^3)
- It should be possible to test stores designed to be used with: wood boilers, solar collectors, heat pumps, gas/oil/pellets boilers and for electrical heaters – or combinations of these.
- Solar plus supplementary heating systems or non-solar heating systems should use the same test sequence.
- The thermal results should be representative of the annual thermal performance, especially for stores used in solar plus supplementary heating systems.
- Incorporate a DHW comfort and/or discharge test into the test sequence.
- The test should be reproducible and should not require sensors within the store.
- It should be less expensive to perform than prEN12977-3.

2.2 Scope of Combitest

- Stores may include or not include an auxiliary heater integrated in the store. If an external auxiliary heater is required then a standard heater will be used, the type chosen by the manufacturer of the store from a list of standard auxiliary heaters, i.e. electrical, oil/gas or wood (manually fired). External auxiliary heating can be connected directly or indirectly through a heat exchanger.
- The store will be connected to an emulated standard heat distribution system, a radiator system with 60/50 (flow/return) temperatures. The manufacturer may specify another type of distribution system if it is essential to the function of the store.
- If the store can be used with a solar collector, a standard collector will be emulated by the testing stand.

- The store(s), including equipment for preparation of domestic hot water will be installed by the manufacturer or designated installer. The auxiliary heater, if included in the store, will also be installed by the manufacturer.
- The maximum size of a store is limited by the specifications of the testing stand.

2.3 Requirements for the Test Stand

The hardware of the testing stand should consist of the following:

- Collector Hardware Simulator (CHS) that can simulate a standard collector of 10-15 m^2 (10 kW). Flow and outlet temperature are controlled.
- Heating System Hardware Simulator (HSHS) that can simulate either a floor or radiator heat distribution system (or combination). Return temperature and flow are controlled. Maximum cooling power is 15 kW.
- Auxiliary Heating Hardware Simulator (AHHS), which can simulate a standard external gas, oil or wood (solid wood fuel or wood chip) auxiliary heater. Auxiliary heating outlet temperature and flow are controlled. Maximum heating power is 30 kW.
- Conditioning circuit. This shall be able to condition the store, possibly in conjunction with other circuit, to a uniform nominal temperature.
- DHW discharge circuit. This shall be able to perform discharges of different flow rates according to a discharge profile.
- Climate chamber able to hold a constant temperature ±2°C.

Table 2.2 and Table 2.1 show the measured quantities for the test stand and the required accuracy of the sensors (including measuring equipment).

Table 2.1: Definition of all the quantities to be measured (if present).

Measured Quantity
Temperature at all inlets and outlets of the store ports
Temperature at inlet and outlet to/from collector loop heat exchanger
Temperature at inlet and outlet to/from an external DHW heat exchanger
Temperature at inlet and outlet to/from the external auxiliary heating heat exchanger loop
Flows in all circuits
Inlet and outlet temperature for DHW
Electrical power for electrical auxiliary heater
Electrical power separately for all controllers and pumps and other electrical items
Temperature of the sensors used by the controllers
Ambient temperature in the room of the testing stand
Gas, oil or wood volume or mass

Table 2.2: Definition of required accuracy of measurements in the testing stand.

Quantity	Accuracy
Absolute temperature	0.1 K
Temperature difference (for heat power calculations)	0.05 K
Volume flow	2 %
Electrical power	1 %
Gas volume	1 %
Oil volume	1 %
Wood mass	1 %

The testing stand should be validated to show that the tests can be reproduced reliably. One store has to be tested twice with exactly the same test sequences and conditions. For the testing stand to be validated, the total energies for all ports and heat exchangers have to be within ±5% of one another, and the derived performance indicators for the Direct Characterisation part of the method have to be within ±3%. This gives a measure of the reproducibility of the test stand but gives no information on systematic errors.

3 The Test Sequence

The development of Combitest has so far been carried out solely using simulations. This is far quicker in the initial stages and was used successfully during the initial design and analysis of the DST testing method [6].

3.1 The Phases of Combitest

The phases of Combitest are shown diagrammatically in Figure 3.1 and descriptively in Table 3.1. The aim of the secondary conditioning is to achieve similar conditions in the store at the start of the core phase to those that will occur at the end of the core phase. The final discharge is used to give a measure of the DHW capacity at that point. The energy content of the store at the end of the test sequence is required in order to perform the necessary energy balance calculations. This can be measured in two ways. The first is to fully mix the store after the final while measuring the temperature in the mixing loop. This is simple, but can result in extra losses that have to be estimated. Alternatively, a conditioning could be performed as is done in the full CEN method. This additionally gives information about the stratification in the store.

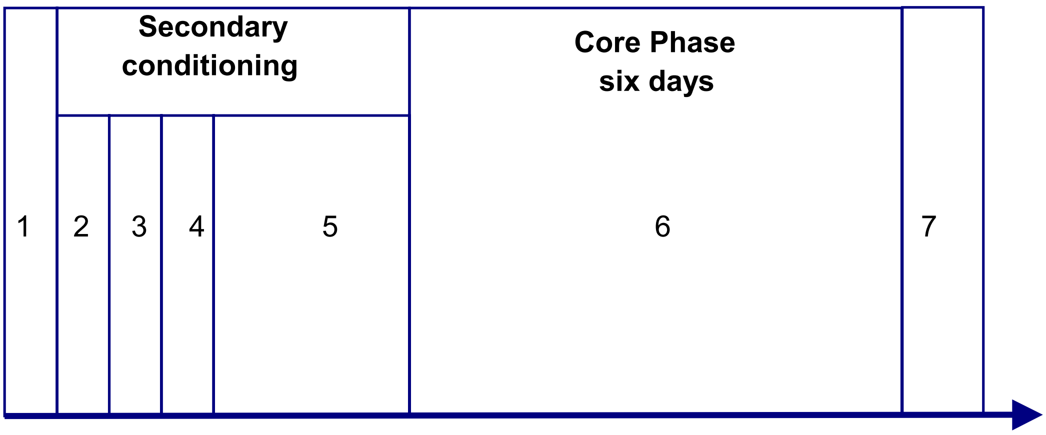


Figure 3.1: The phases of Combitest.

Table 3.1: Description of the seven parts of Combitest.

Nr	Name	Period [h]	Description
1	Conditioning	$\rightarrow 0$	Conditioning of the store to a uniform temperature of 20°C.
2	Secondary-	$0 \rightarrow 8$	Full charge of store with winter auxiliary heater. Automatic heaters on from this point onwards.
3	...	$8 \rightarrow 20$	(Constant) space heating discharge.
4	condition-	$20 \rightarrow 24$	DHW comfort test.
5	ing	$24 \rightarrow 48$	Final conditioning.
6	Core Phase	$48 \rightarrow 192$	Six days of realistic conditions (climate and load).
7	Final Discharge and mixing	$192 \rightarrow ?$	Discharge of DHW until the DHW outlet temperature goes below 30°C, followed by mixing of the store contents or alternatively conditioning to 20°C.

3.2 Details of the Latest Version (v2.1)

The first version of the test sequence was developed according to the ideas described in section 1.1. This had one day of secondary conditioning and the following days chosen in this order: winter (days 7, 32), spring/autumn (days 280, 281), summer (days 168, 154). This did not give very good results in terms of having the same energy in the store at the start and end of the six-day core phase, i.e. dQ_s was not small. The secondary conditioning was changed to have two days instead of one, and the order of the days in the core phase was altered. The contents of the second day of secondary conditioning were adjusted to give low values of dQ_s. In addition the spring/autumn period was split into two parts in order to have a period of relatively high load at the end of the sequence. The final sequence of days was thus: 7, 32, 280, 168, 154, 281.

The conditions during the secondary conditioning are shown in Figure 3.2 and the details of the DHW comfort test are shown in Table 3.2. The comfort test is based on an existing German standard, DIN 4708 [7], using a standard load for a single family, but it has been adapted to fit the time step of the simulations and the inlet temperature used in the test (10°C). The second day of the phase has a relatively large solar insolation (slightly unrealistic in this case) during the middle of the day in order to give sufficient solar charging of the store. This was found necessary for larger stores in order to achieve a low dQ_s. The DHW discharge profile on this second day is the second day of the two-day profile defined in Table 3.3.

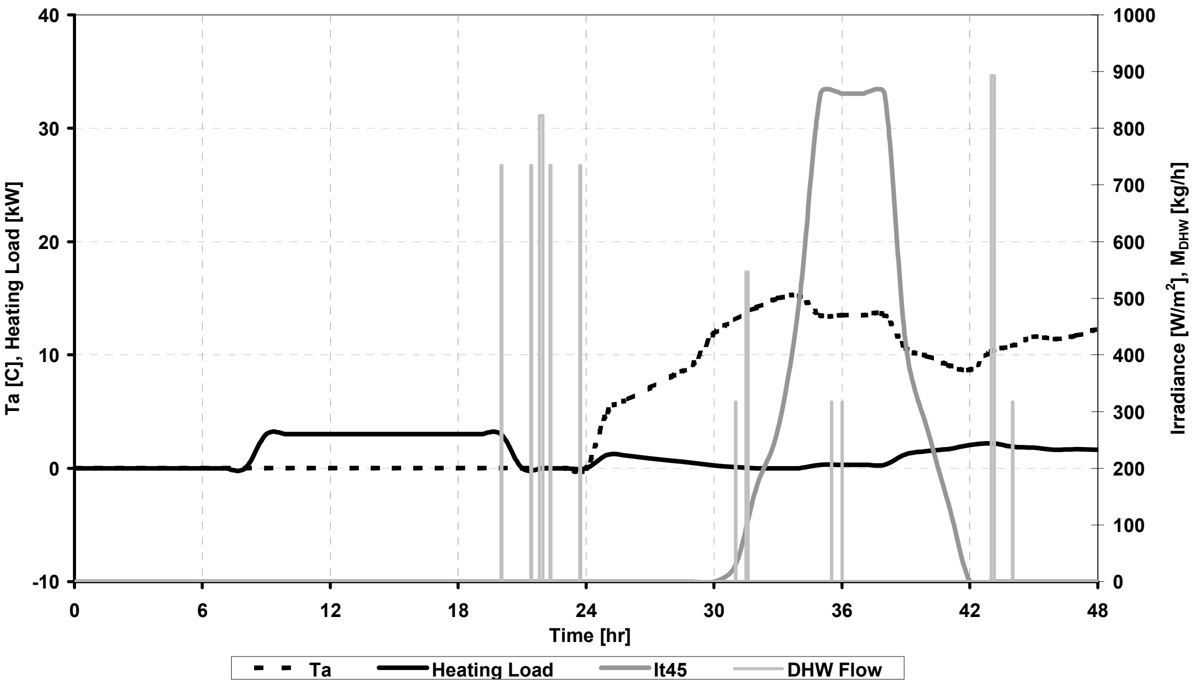


Figure 3.2: Conditions during the secondary conditioning phase of Combitest.

Table 3.2: Details of the DHW discharges during the DHW comfort test that is applied during the secondary conditioning.

Time [h]	Period [h]	Energy [kWh]	Flow [kg/h]
20.00	0.05	1.49	734
21.40	0.05	1.49	734
21.80	0.18	5.85	822
22.30	0.05	1.49	734
23.70	0.05	1.49	734

The conditions for the main part of the test, the core phase, are shown in Figure 3.3. The DHW discharge profile is a two-day profile based on definitions for a bath, long and short showers and short discharges, and adapted for a 0.025 hour time step. This profile, repeated three times during the core phase, is detailed in Table 3.3. It gives a load of 198 litres per day, with an inlet temperature of 10°C and outlet temperature of 45°C.

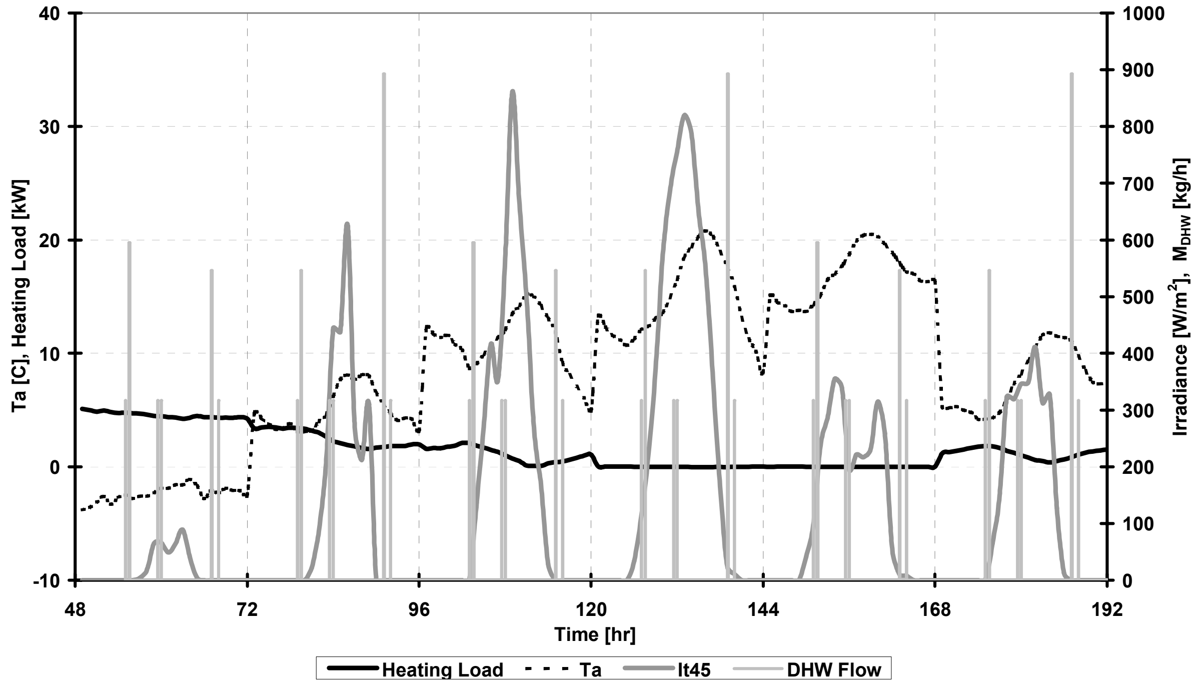


Figure 3.3: Conditions during the core phase of Combitest.

Table 3.3: Details of the two-day DHW discharge profile used within the core phase of Combitest, and the second day of the secondary conditioning. The second day of this profile is used on the second day of the secondary conditioning.

Time [h]	Period [h]	Energy [kWh]	Flow [kg/h]
7.00	0.025	0.32	317
7.50	0.150	3.63	595
11.50	0.025	0.32	317
12.00	0.025	0.32	317
19.00	0.100	2.22	546
20.00	0.025	0.32	317
31.00	0.025	0.32	317
31.50	0.100	2.22	546
35.00	0.025	0.32	317
36.00	0.025	0.32	317
43.00	0.150	5.44	893
44.00	0.025	0.32	317

4 Test Evaluation

4.1 Direct Characterisation

The direct characterisation is based on input-output relations for the core phase of the test sequence (see Figure 3.3).

4.1.1 Proposed Performance Indicators

The proposed performance indicators that are to be calculated from the test are described in Table 4.1. The method of calculation is defined in the following section.

Table 4.1: Description of the proposed performance indicators for Combitest.

Symbol	Description
F_{SAV} [%]	Fractional energy savings for the core phase compared to a theoretical reference conventional (non-solar) heating system with the same load. F_{SAV} is a measure of the solar energy performance.
η_{store} [%]	Efficiency of the store during the core phase, determined by the ratio of the total load to the total charging energy.
$UA_{s,loss}$ [W/K]	Overall heat loss coefficient for the store. This is an alternative to η_{store}.
$Q_{cap,cg}$ [kWh]	Effective heat capacity in the store for the main auxiliary heater, starting from a uniform 20°C in the store. This is derived from the start of the secondary conditioning phase.
$Comf_{DHW}$ [-]	DHW comfort indicator from the comfort test. The discharge level that the store can meet with the thermostat settings used for the core phase. This is derived from the DHW comfort test (based on DIN 4708), which is applied in the middle of the secondary conditioning phase. The winter auxiliary heater is switched on during the comfort test. The store either satisfies the load or does not, i.e. it gets a level of 1 or 0. A separate test would be required if a higher level is to be tested for.
$dQ_{s,end}$ [kWh]	Difference in energy content of the store between start and end of the core phase. This is a measure of the quality of the test, not the store.
$Q_{cap,DHW}$ [kWh]	Amount of DHW load that can be discharged while maintaining at least 40°C at the outlet. Determined from the final discharge after the end of the core phase.
t_{cgint} [h]	The time between the first and second charges of the store at the start of the core phase, when the load is at its peak. This value, together with $Q_{cap,cg}$ is a measure of how well the store is utilised.

A further performance indicator ($E_{aux,y}$) has been proposed in Task 26. This is included in this report so that the results for it can be compared with those for the original equivalent indicator, F_{sav}.

4.1.2 Calculation of the Performance Indicators

The following equations and definitions describe how the performance indicators are to be calculated from the measured data.

The following general nomenclature is used. Q is used for energy transferred to/from the store. Energy transferred to the store is given a positive sign, and energy removed from the store a negative sign. Suffices $_{sc}$, $_{core}$ and $_{all}$ refer to secondary conditioning phase, core phase and whole test sequence respectively. Suffices $_{s}$, $_{loss}$, $_{b}$, $_{aux\ el}$, $_{DHW}$, $_{hs}$ and $_{sol}$ refer to store, heat losses, boiler (auxiliary heater), auxiliary electrical heater, domestic hot water, space heating system and solar respectively.

Equ. 4.1
$$dQ_{s,end} = Q_{s,end} - Q_{s,tc0}$$

Where:

$Q_{s,end}$ energy contents of the store relative to 20°C at the end of the core phase.

$Q_{s,tc0}$ energy contents of the store relative to 20°C at the start of the core phase.

Equ. 4.2
$$\eta_{store} = \frac{-(Q_{DHW,core} + Q_{hs,core})}{Q_{sol,core} + Q_{b,core} + Q_{auxel,core} - dQ_{s,end}}$$

Equ. 4.3
$$UA_{s,loss} = \frac{Q_{loss,all}}{dTt_{loss,all}}.$$

Where:

$Q_{loss,all}$ Heat losses from the store during the whole test.

$dTt_{loss,all}$ Time integrated temperature difference between the average tank temperature and the surroundings, for the whole test sequence. This must be calculated by the measurement program using the following equations. *The measurement program will require an estimation of the volume of the store and $UA_{s,loss}$ in order to be able to calculate these values*.

The following four equations describe how the average temperature in the store can be calculated based on an energy balance for the store. Suffix $_{t}$ is for time t during the sequence.

Equ. 4.4
$$Q_{s,t} = Q_{b,t} + Q_{auxel,t} + Q_{sol,t} + Q_{DHW,t} + Q_{hs,t} + Q_{loss,t}$$

The energy content of the store at time t ($Q_{s,t}$) is determined from an energy balance, and the only quantity not measured ($Q_{loss,t}$) must be estimated using an estimated value for $UA_{s,loss}$ and the time integrated temperature difference $dTt_{loss,t}$. The average temperature in the store is calculated from the energy content and the estimated volume of the store.

Equ. 4.5 $$Q_{loss,t} = UA_{s,loss} \cdot \int_0^t (dT_{loss,t})\,dt$$

Equ. 4.6 $$dT_{loss,t} = T_{s,t} - T_{s,amb}$$

Equ. 4.7 $$T_{s,t} = \frac{Q_{s,t} \cdot \left[3600 \cdot \frac{kJ}{kWh}\right]}{V_s \cdot \rho_s \cdot Cp_s}$$

In order to calculate the fractional energy savings (F_{SAV}) of the system, the energy used by a theoretical conventional (non-solar) heating system to supply the same load, must be calculated. The same method is used as for calculating this quantity for the annual simulations and is based on a method used in prEN12977-2 [3]. There are two exceptions:

- A temperature of 20°C is used instead of 15°C for the ambient temperature around the store. This is done as most test methods use 20°C as the reference temperature.
- The conventional (reference) system supplies heat to the heating system and to DHW. The heat losses are assumed to be the same as those calculated by the method in prEN12977-2 for a purely hot water system with the same load. In prEN12977-2 there is no space-heating load, so this part is an extension to the method described there.

F_{SAV} is calculated by:

Equ. 4.8 $$F_{SAV} = 100 \cdot \left[1 - \left(\frac{\frac{Q_{auxel,core}}{\eta_{el}} + \frac{Q_{b,core} + Q_{b,rad,core}}{\eta_b}}{E_{conv}}\right)\right]$$

Where:

Equ. 4.9 $$E_{conv} = \frac{Q_{b,rad,core,conv} + Q_{DHW,core,conv} + Q_{hs,core,conv} + Q_{loss,core,conv}}{\eta_{conv}}$$

and:

$Q_{loss,core,\ conv}$	Losses of the hypothetical store in the conventional system during the core phase of the test. The calculation for this quantity is not described here, but can be found in prEN12977-2 [3], and is for the six-day period.
$Q_{b,rad,core,conv}$	The energy that is supplied directly to the heating system (radiators) from the boiler. This is required as certain systems supply some energy in this manner and the stores in this system are based on this concept.
$Q_{DHW,core,conv}$	Energy supplied to DHW in the core phase for the tested store.
$Q_{hs,core,conv}$	Energy supplied to space heating in the core phase for the tested store.
η_{conv}	Efficiency of the boiler/auxiliary in the conventional heating system.
η_b	Efficiency of the boiler/auxiliary in the solar heating heating system. In this work this was the same (85%) as that for the conventional heating system.
η_{el}	Efficiency of the electricity production and heater combined. This was assumed to be 100% for this calculation.

The final performance indicator, $E_{aux,y}$ is calculated by:

Equ. 4.10

$$E_{aux,y} = E_{aux,core} \cdot \frac{Q_{load,y}}{Q_{load,core}}$$

Where:

Equ. 4.11

$$Q_{load,core} = Q_{b,rad,core} + Q_{hs,core} + Q_{DHW,core}$$

Equ. 4.12

$$E_{aux,core} = \frac{Q_{auxel,core}}{\eta_{el}} + \frac{Q_{b,core} + Q_{b,rad,core}}{\eta_{b}}$$

$Q_{load,y}$ is the total annual load for the climate and load used in the test sequence. In this study the value calculated by the annual simulation model was used here. The nominal value was 16540 kWh.

Note that parasitic energy is not included in these equations. Parasitic energy is the extra energy, usually electrical energy for pumps and controllers, that is required by the solar (or non-conventional) system and that is not required by the conventional system. This value could be incorporated into $Q_{aux,el}$ or an extra term can be added to the equation.

4.2 Annual Calculation

This is made in a similar manner to that used in the Component Test and System Simulation (CTSS) test method, i.e. a detailed parameter identification of a simulation model using dynamic fitting, followed by an annual simulation using the same model. [3]

4.2.1 Test Sequences

In the full CEN method, there are a number of separate test sequences, each specifically designed to get data about a particular port or heat exchanger with as little interaction with other ports and heat exchangers as possible. This means that no two circuits are active at the same time. This leads to the minimum amount of correlation between derived parameter values. With Combitest, the opposite is the case. It has one major test sequence, with several circuits active at the same time during different phases of the test, and this test sequence alone was used for parameter identification. Extra test sequences, either of a specific nature as with the full CEN method, or of a more general (complex) nature could also be made, resulting in more measurement data and presumably more reliable parameter values. This was however not studied in this work.

5 Method

5.1 Direct Characterisation

All results presented here are results of simulations. The test sequence described in the previous section was used as input data to the system model, and this was then simulated with the sequence. The system model included a collector, simple boiler model where required, valves, controllers, loads and of course the store model. A complete system is necessary in order to have realistic conditions for the store. These equate to the standard components that are to be emulated in the test stand for Combitest.

5.1.1 Models

The components, other than store, and their parameter values were basically the same for all systems, apart from a few exceptions. One exception is the system with store 1 using a boiler, where a different charging strategy involving two charge zones in the store was simulated. Other exceptions are the collector flow rate and control values. The collector flow rate was varied according to the type of collector heat exchanger as stores 1 and 2 are designed for lower collector flows than store 3. The controller for the collector was the same in all cases, a simple on/off controller with hysteresis, but the start and stop conditions varied depending on the collector flow.

The store models and their parameters are based on those identified with the full CEN method and some small variations from these.

Table 5.1 shows the most important parameters and their values for the external components.

Table 5.1: Summary of the main collector and piping parameter values used in systems simulated for Combitest and for annual simulations with the same model. TRNSYS collector model Type 132, the QDT model was used [8].

Component/Parameter	Value
Collector (type 132)	
Area	10 m^2
Zero loss efficiency	0.8
Heat loss coefficient	3.5 $W/m^2.K$
Temperature dependence of heat loss coeff. (second order term)	0.015 $W/m^2.K^2$
Slope	45°
Incidence angle modifier (b_0)	0.18
Collector piping (one pipe cold side, one hot side)	
Dimensions of each pipe	15 m x 0.01m diameter
Ambient temperature (constant)	20°C
Heat loss coefficient	6 $W/m^2.K$

5.1.2 Comparison with Annual Results

The models used for simulating Combitest were adapted to run for a complete year. The changes made were:

- Climate changed to Zurich (Meteonorm)
- Space heating load changed to a load file created by simulating the IEA-SHC Task 26, 100 kWh/m^2 house for the Zurich climate.

All other details of the annual model were the same. The method for calculating the fractional energy savings for the year was the same as that used elsewhere in the project.

5.2 Annual Calculation

5.2.1 Models and Programs Used

The store model used was TRNSYS Type 140 [9]. The simulation program used was TRNSYS and the fitting program was DF [10]. DF uses a gradient algorithm for the fitting process. A link program is required between DF and TRNSYS, and in this project the program FITTRN was used [11]. In the fitting procedure no models other than the store model were used.

5.2.2 Inputs to the Model and Objective Function

The model that was used for simulating Combitest was also used to create synthetic test data for Combitest, i.e. the mass flows, inlet and outlet temperatures for all ports and heat exchangers were printed out to files for each time step of 0.025 h. The files were then joined together in a spreadsheet and a single file with all values was created. A new model, used specifically to identify parameters using DF, was then created and used for parameter identification in the same way as for the full CEN method. The inputs to the store model were the mass flows and inlet temperatures from the data file described above.

The program DF compares two values (objective values), printed in columns in a data file: the measured value and the simulated value. Here the sum of the absolute heat transfer rates for all ports and heat exchangers was used for this. Absolute values, i.e. magnitudes, were used resulting in a sum and not a net flux for the store.

The measured heat transfer rates for each circuit were calculated using the inlet mass flows and temperatures together with the outlet temperatures, all data coming from the input data file. The simulated heat transfer rates used were those calculated by the model (Type 140), which has them as outputs from the model. The same thermodynamic properties (density and heat capacity) were used in the parameter identification model, in the model used to create the synthetic data and in the calculation of measured heat transfer rates.

5.2.3 Selection of Parameters to Identify

A selection was made of which parameters to identify before the identification process was performed. This selection was based on the results obtained for the same store using the full

CEN method and was specific for the store. Normally, preliminary identification runs are required in order to judge which parameters need to be identified in the final process. All parameters were identified at the same time, as recommended in the full CEN method. See section 6.2 for more details.

5.2.4 Verification of Results and Comparison with Annual Results

For a verification of the results (identified parameter values) the same model was used but with another test sequence that was used for verification when applying the CEN method. From the results of this simulation, relative errors for transferred energy and power were calculated as described in the full CEN method. These are a measure of how well the verification sequence has been simulated. Relative error values were also calculated for the simulation using Combitest data, i.e. the data used in the identification process.

An annual simulation was also performed using the store parameters identified using the Combitest data.

6 Results

6.1 Direct Characterisation

6.1.1 Description of Stores Tested

Three basic stores were tested for Combitest with very different characteristics and internal components. They are referred to simply as stores 1, 2, 3 etc. A number of variations of these were also simulated in order to test the ability of Combitest to differentiate between them. One important parameter that was varied was the store volume. This is important, as Combitest is sensitive to the size of the store as larger stores have larger capacity and thus take longer to discharge than smaller ones. There is a larger possibility of energy stored during one “season” of the sequence being available in the next “season” in a manner that does not occur in the whole year. Stores named 1 and 2 are the same apart from the auxiliary source, 1 having a boiler attached whereas store 2 has an internal electrical heater. Store 3 has a completely different construction. Stores 4 to 10 are variations of a third store concept, with varying values for inlet/outlet heights, insulation and volume. Stores 9 and 10 are in addition simulated both in Combitest and the annual simulations as being connected to a solid-wood boiler.

6.1.2 Calculated Performance Indicators

The performance indicators, calculated for the 10 stores, are shown in Table 6.1 together with the total volume of the store including heat exchangers. The last three quantities are derived directly from measured data (actually simulated in this work), whereas the first five are calculated using the equations defined in section 4.1.

*Table 6.1: Performance indicators for 10 stores calculated from simulated Combitest data. * means the value could not be determined.*

Name	Volume [m^3]	F_{SAV} [%]	$E_{aux,y}$ [kWh]	η_{store} [%]	$UA_{s,loss}$ [W/K]	$dQ_{s,end}$ [kWh]	$Q_{cap,cg}$ [kWh]	t_{cgint} [h]	$Q_{cap,DHW}$ [kWh]
1	0.773	22.6%	15702	95.9%	-2.59	1.08	20.9	0.650	-11.4
2	0.773	34.5%	15599	95.9%	-2.78	-0.17	11.0	0.200	-10.9
3	0.476	14.3%	17489	93.2%	-2.13	-1.41	12.8	0.575	-7.1
4	0.763	19.6%	16337	94.5%	-3.32	-1.29	15.8	0.350	-10.1
5	0.763	22.3%	15778	97.3%	-1.57	-0.66	14.3	0.275	-6.6
6	0.763	22.0%	15843	97.2%	-1.57	-0.89	15.6	0.250	-7.2
7	1.513	23.0%	15696	96.0%	-2.37	-0.60	31.7	0.275	-18.5
8	2.263	20.8%	16194	94.8%	-3.14	5.53	48.2	0.325	-31.0
9	1.263	11.0%	18180	91.6%	-3.68	-0.13	95.0	*	-66.0
10	2.013	12.0%	18117	91.7%	-3.66	-1.70	151.9	*	-76.1

The stores, together with their particular system configuration, have very different performances. System 2 has much higher savings than system 1 partly because the efficiency of its electrical heater has been defined as 100% whereas the boiler in 1 had an efficiency of 85%.

The capacities of the stores, $Q_{cap,cg}$, are dependent on the volume of the store heated by the auxiliary heater and of the set temperature. There is a significant range here, with the largest values for those attached to solid-wood boilers that heat up the entire store. This applies to both the charging and discharging (DHW). The charge interval, $t_{cg,int}$, is also dependent on this volume, but is also dependent on how the ports for space heating are placed in relation to the boiler ports. Stores 1 and 3 have longer intervals, store 1 due to the large charge capacity and store 3 due to the fact that the space-heating load is supplied both from the store and directly from the boiler, and thus not all the load is removed from the store. Stores 7 and 8 have relatively short charging intervals despite of the fact that the charge capacity is large. This indicates poor design. The charging interval for the wood boilers is shown as * as it could not be determined because the charging strategy chosen for the simulation allowed charges only during at 7 am and 7 pm. Another measure for this time interval, or another strategy for charging with wood boilers, is required if this measure is to be meaningful.

The energy difference between start and end of the core phase, $dQ_{s,end}$ varies from –1.7 to 5.5 kWh, which is –0.6% to 2.0% of the total load of 268 kWh.

6.1.3 Comparison of Calculated and Used Heat Loss Coefficients

The heat loss coefficient for Combitest is calculated assuming uniform loss from the store, whereas the heat loss coefficients used in the simulations are non-uniform. Figure 6.1 shows the comparison of the calculated values of heat loss coefficients based on Combitest data ($UA_{s,loss,combi}$) and the sum of the individual heat loss coefficients used in the simulations ($UA_{s,loss,sim}$). These show a reasonable trend, but the value calculated from Combitest is consistently lower. This is not very surprising as the coefficients used in the simulation have one component for the sides and one for the bottom. The coefficient for the bottom, as identified, is often higher per unit area as the insulation is relatively poor there. However, the actual heat losses from the bottom are in general relatively low as the temperature is lower there. Thus a heat loss coefficient for the whole store, assuming uniform heat loss per unit area, is usually less than the sum of the components for the side and the bottom, as is the case here. The results therefore look very reasonable.

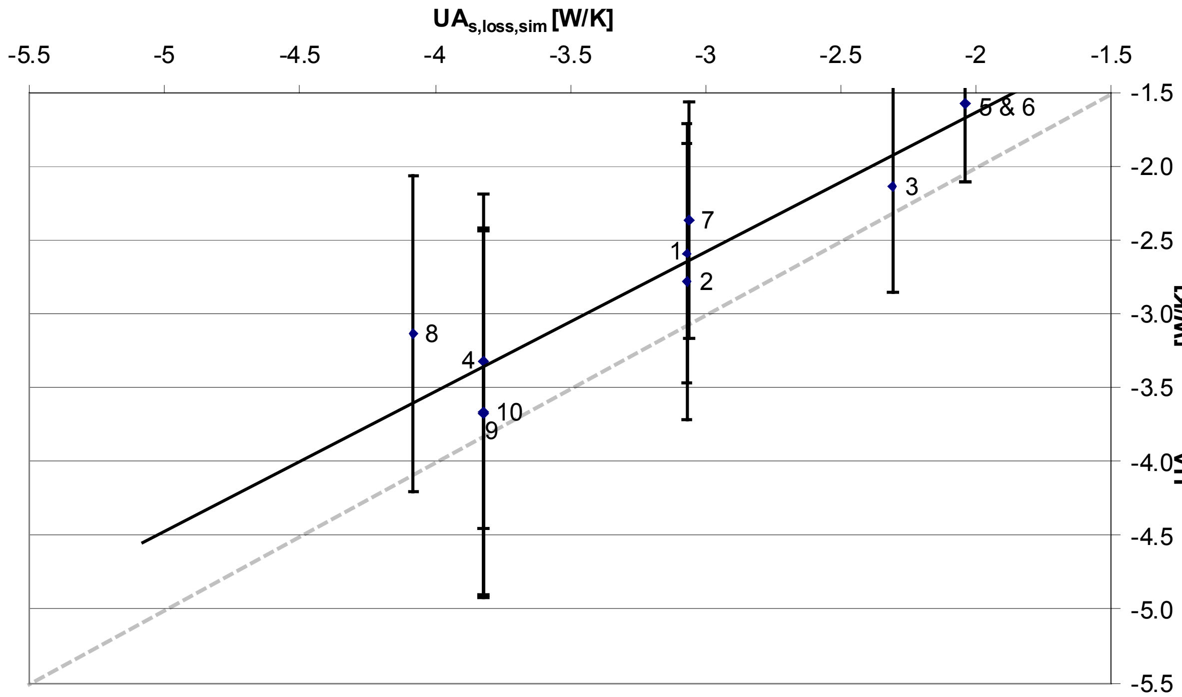


Figure 6.1: Comparison of the calculated heat loss coefficient from Combitest data ($UA_{s,loss,combi}$) and the sum of the partial heat loss coefficients used in the models ($UA_{s,loss,sim}$). The dashed line indicates what perfect identification of $UA_{s,loss,sim}$ would give. The uncertainties are those shown in section 7.

However, in a real test, the data used to calculate the heat loss coefficient are estimated by the measurement program. The program requires estimates for both the volume and the heat loss coefficient itself in order to calculate the average store temperature from an energy balance (see 4). In addition, the uncertainties in measurements will also lead to relatively large uncertainties in the calculated value as the heat loss (energy) is calculated as the remainder of an energy balance and is only 7-20 kWh compared to the total load of 270 kWh. The uncertainties shown are very large and are of the order of ±30%. The equivalent uncertainty for the store efficiency is ±1.9%, again very large as the variation in efficiencies for the 10 stores was 91% – 97%. Halving the uncertainty of the measured values roughly halves the uncertainty of the derived quantities. See section 6.1 for more details.

Figure 6.2 shows a comparison of the two performance indicators related to heat loss: store efficiency and heat loss coefficient. Here, there is some relationship between the two quantities, but the scatter is large. Some form of relationship is to be expected as the conditions for the test are always the same, resulting in the same load energy for all cases. The energy input to the store is determined by this (constant) load and the losses. The losses are in turn dependent directly on the heat loss coefficient and the average temperature level in the store. The latter is a characteristic of the system, and as this varies in the systems (stores) simulated, some scatter is to be expected. Store 3 is used in a system where only a relatively small fraction of the space-heating load is delivered from the store. This reduces the energy throughput in the store while still maintaining roughly the same losses as would have occurred if all the space heating load had been delivered by the store. Due to the definition of η_{store}, this results in a relatively low value compared to those for the other stores.

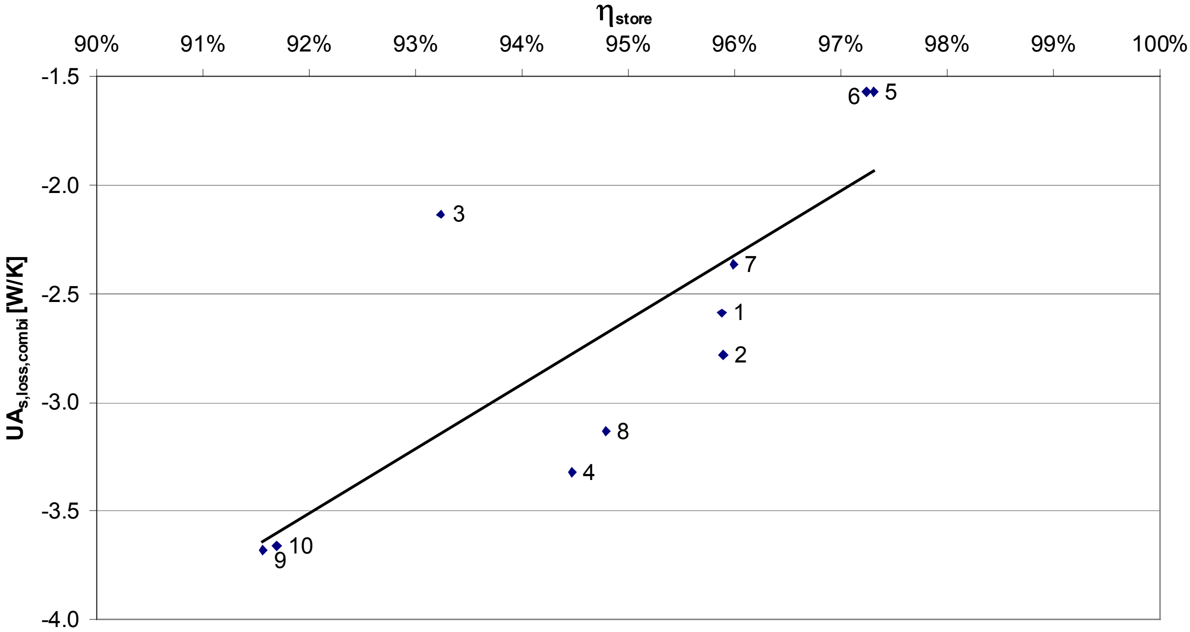


Figure 6.2: Comparison of the store efficiency (η_{store}) and the heat loss coefficient calculated from Combitest data ($UA_{s,loss,combi}$).

6.1.4 Comparison with Annual Simulations

Figure 6.3 shows how the fractional energy savings calculated for Combitest compare with those for an annual simulation. It is clear that there is a good correlation between the two, but that the values for Combitest are consistently higher than the annual values. A correction factor could be applied to the calculated value in order to get a value that is representative for the whole year. For the figure shown, the factor would be 0.81 with a standard deviation of 0.06. The other alternative would be to change the conditions of the test sequence in order to get a more representative value for F_{SAV}. Note that this factor is only for this climate. It is not certain that the same factor would be applicable for other climates and loads.

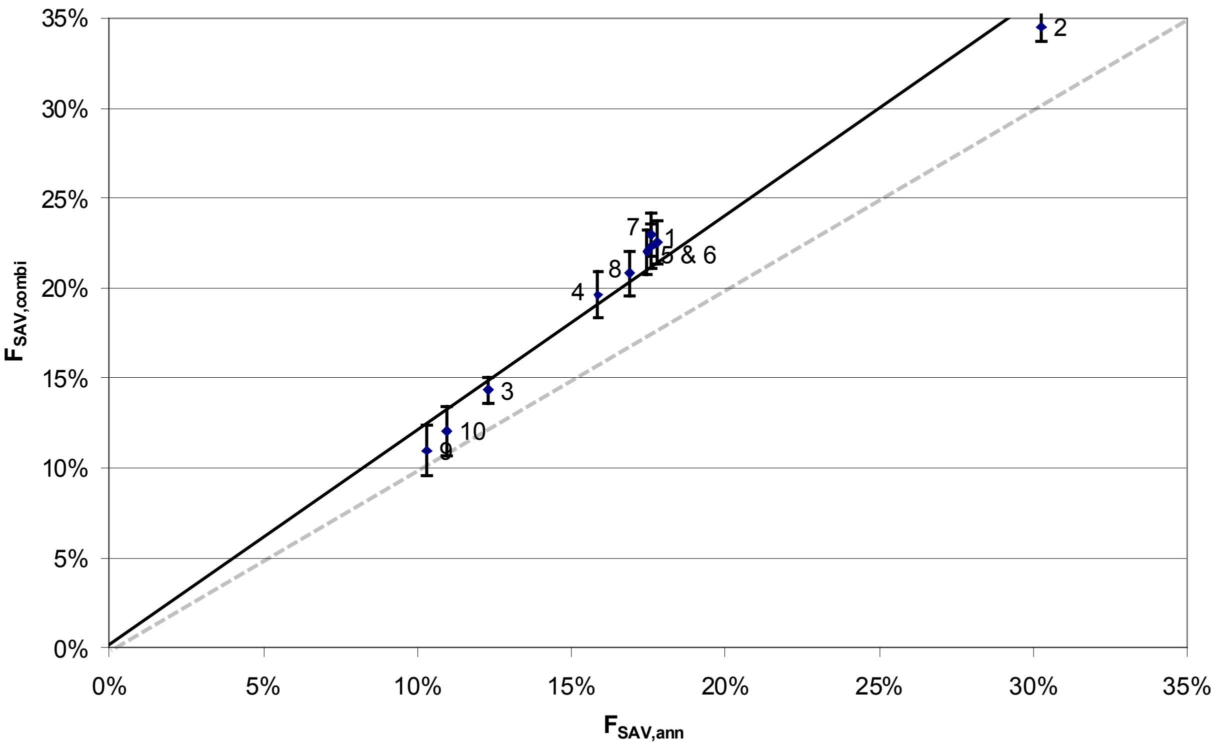


Figure 6.3: Comparison of fractional energy savings calculated for Combitest ($F_{SAV,combi}$) with that calculated for the same system for a whole year ($F_{SAV,ann}$). The dashed line indicates what perfect prediction of $F_{sav,combi}$ would give. The uncertainties are those shown in section 7.

Figure 6.4 shows a comparison of the final performance indicator $E_{aux,y}$ with the auxiliary energy use for the equivalent annual simulation $E_{aux,ann}$. Again it is clear that there is a good correlation between them. However, the values should ideally be the same, shown diagrammatically with the dashed line, and it is clear that this is not the case. Due to the good correlation between the indicator and the actual value it should be possible to use a correction factor based on the value. This however, was not tried.

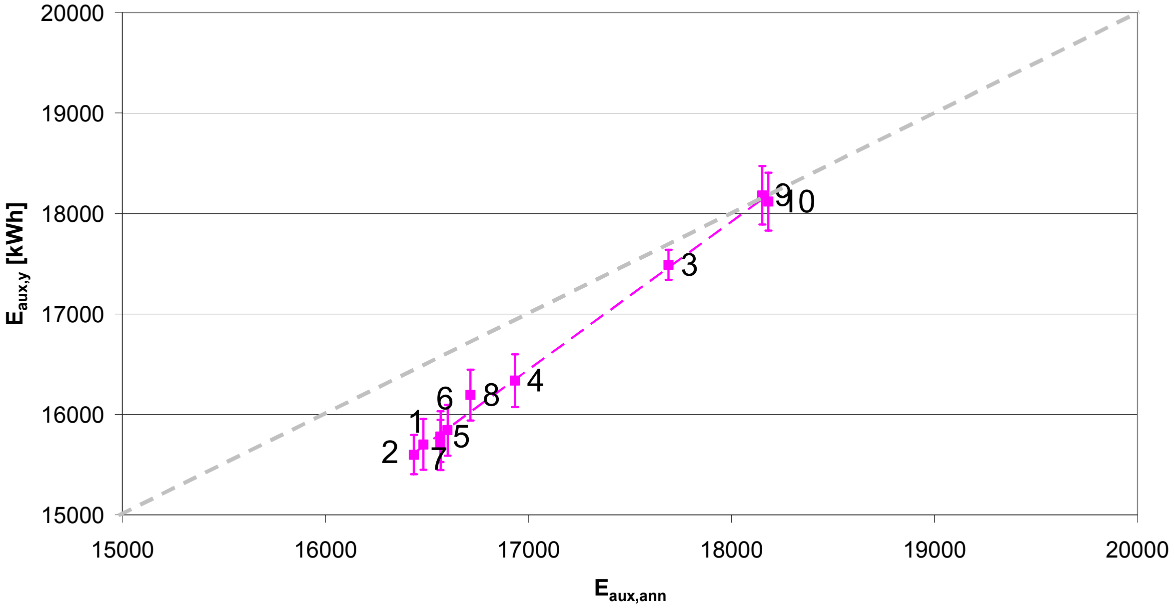


Figure 6.4: Comparison of calculated auxiliary energy use ($E_{aux,y}$) from Combitest with that from the annual simulations of the same system. The dashed line indicates what perfect prediction using $E_{aux,y}$ would give. The uncertainties are those shown in section 7.

6.2 Annual Calculation

The annual calculation part was only performed for store 1, using data that was synthetically produced using the parameter values identified with the CEN method. The process for identification followed the same procedure as used in the full CEN method. All parameters were identified together.

6.2.1 Comparison of Identified Parameters for Combitest with Those for CEN

Certain parameters, identified for the full CEN method, were not identified for Combitest. Two of these were: the maximum primary flow in the DHW unit, set temperature of the DHW unit. Several heights could not be identified, as DF gave a zero Hesse matrix. This was probably due to insufficient data, or due to the value being too close to the range limits. These were: inlet and outlet heights for the collector stratifier/heat exchanger, outlet height for the DHW unit. These values were set to the geometric heights.

Table 6.2 shows a comparison of the identified parameters for the full CEN method and for Combitest. It should be noted that the parameters identified for CEN were used in the simulation to create the synthetic Combitest data. If the identification process for Combitest were ideal, the same parameter values should be identified. This, however, is not the case as is obvious from the table. All heights are identified within one node (0.01) of the CEN values. Even the estimated heights used as fixed values are within 2 nodes. The volume is also very close to the CEN value, being only 0.4% different. The identified heat loss coefficients are both larger than the CEN values, but they have the same standard deviations as when identified with the full CEN method. No explanation of this could be found.

Both the collector and DHW unit heat exchangers were identified very differently. In the case of the collector heat exchanger, the temperature dependency was fixed to zero and no flow dependence was identified. This is not surprising as there was no flow variation in the synthetic Combitest data. Thus UA-value for the heat exchanger is fixed. Despite different parameter values, at normal flows and operating temperature the UA-values for the CEN and Combitest parameters are very similar. Indeed they are the same for a flow of 125 kg/h (the flow used in Combitest) and an average temperature of 47°C. For the DHW unit, only a very small flow dependency was identified, but the standard deviation is low. This is probably due to limited operating conditions for the unit during Combitest. Again, for the operating conditions found in Combitest, which should be representative for the year, the values are similar. In fact they are the same when the combined primary and secondary flow is 1300 kg/h.

Table 6.2: Comparison of parameter values identified for the full CEN method and those identified from Combitest. The identification used synthetic data created with a model using the full CEN method values. The grey scale indicates the standard deviation of the identified value. Parameters fixed for the CEN identification are not included in the table.

Parameter	Unit	CEN	Combitest
General			
tank volume (excl. heat exchangers)	m^3	0.767 ±0.001	0.774 ±0.002
overall heat loss coefficient - sides	kJ/h.K	9.28 ±0.27	10.45 ±0.27
overall heat loss coefficient - bottom	kJ/h.K	1.78 ±0.32	3.48 ±0.35
Solar Heat Exchanger			
inlet height	-	0.927 ±0.014	0.90 (fixed)
outlet height	-	0.012 ±0.027	0.00 (fixed)
base UA-value (UA_0)	kJ/h.K	76.5 ±26.3	1666 ±96
b1	-	0.119 ±0.074	0.000 ±0.017
b3	-	0.907 ±0.103	0.0 (fixed)
Factor for secondary flow in stratifier		7.44 ±0.18	7.01 ±0.14
Boiler Connections			
inlet height	-	0.709 ±0.028	0.719 ±0.001
outlet height	-	0.463 ±0.005	0.479 ±0.001
Heating System Connections			
inlet height	-	0.044 ±0.015	0.054 ±0.005
outlet height	-	0.778 ±0.012	0.784 ±0.001
heat exchanger base UA-value	kJ/h.K	19.8 ±21.3	21.0 ±0.3
DHW Preparation			
outlet height	-	0.97 ±0.002	0.98 (fixed)
Base UA-value	kJ/h.K	70.87 ±1.61	4812 ±116
Flow exponent for UA-value	-	0.693 ±0.004	0.104 ±0.004
Grey scale for standard deviations			
<0.01 for heights, <0.01 for b-factors for heat exchangers, <1% for others			
<0.03 for heights, <0.05 for b-factors for heat exchangers, <5% for others			
<0.05 for heights, <0.20 for b-factors for heat exchangers, <20% for others			
>0.05 for heights, >0.20 for b-factors for heat exchangers, >20% for others			

Table 6.3 shows the parameters with high cross correlations identified with the synthetic Combitest data. This shows slightly higher correlations than were found using the CEN test measurement data. This is to be expected as the test sequences for the full CEN method are specifically designed to minimise the correlations.

Table 6.3. Summary of relatively high correlations found during the identification from Combitest data.

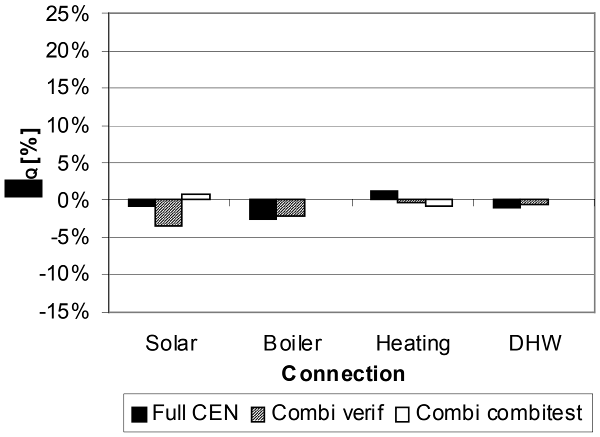
Correlation	Correlated Parameters
>0.9	Base UA-value for the solar heat exchanger and its b1factor
0.8-0.9	Base UA-value and the flow factor for the external DHW unit
0.5-0.8	Inlet and outlet heights for the boiler
	Inlet height for the boiler and outlet height for the space heating
	Heat loss coeff. for the bottom and base UA-value for solar heat exchanger
	Heat loss coefficient for the bottom and the b1 factor for solar heat exchanger

6.2.2 Verification

Figure 6.5 shows the results of the verification of the parameters identified from Combitest. Also shown are verification results for the values identified with the full CEN method but with the same verification sequence as used for Combitest. Both sets are good, with all relative energy levels below 3% apart from for the collector circuit using the Combitest values. Here the error is only slightly larger than 3%. The relative power errors are also quite good, and the errors for the Combitest values are only very slightly larger than those for the CEN values. The collector circuit is again the weakest one, although it is still good.

Lastly, the results for a resimulation of the Combitest sequence are given, labelled Combi Combitest in Figure 6.5. These would be zero, if the same CEN parameter values were used for the resimulation. The results show a very good agreement, again apart from for the collector circuit.

This shows that the identification is good.



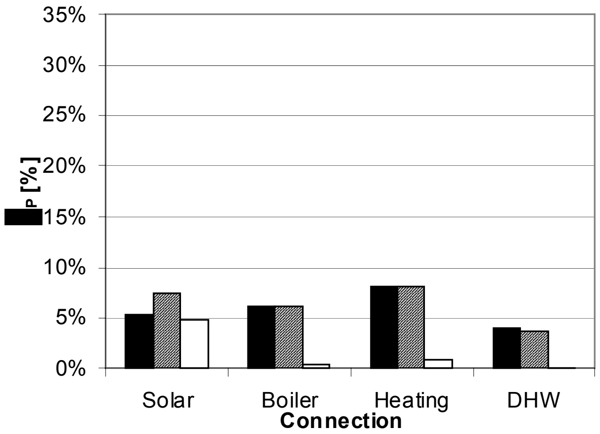


Figure 6.5. Relative errors (ε_P and ε_Q) for the verification sequence for the parameter sets from the full CEN and Combitest methods. Also shown are the relative errors for the Combitest sequence itself.

6.2.3 Results of Annual Calculation

The same system model was used with both the CEN identified parameter values and the Combitest identified ones. The fractional energy savings for the CEN parameters was 17.2% and 16.9% using parameters identified from Combitest, giving a value of -1.7% for dF_{SAV}. This is a very small difference, and is in spite of the fact that the losses were over 100 kWh greater (14%) when using the Combitest parameters. This is because half of these added losses were supplied by solar.

Table 6.4: Results of annual simulations using the CEN and Combitest derived parameter values for store 1.

	F_{SAV} [%]	Q_{sol} [kWh]	Q_b [kWh]	Q_{hs} [kWh]	Q_{DHW} [kWh]	Q_{loss} [kWh]
CEN	17.2%	3317	14010	-13550	-2935	-820
Combitest	16.9%	3367	14070	-13550	-2931	-938

7 Uncertainty Analysis

The uncertainties of the performance indicators were calculated using simple assumptions on the uncertainties of the measured quantities. They have been calculated using the Engineering Equation Solver program (EES) [12], which was also used to calculate the performance indicators themselves. The method used by EES for determining this uncertainty propagation is described in NIST Technical Note 1297 [13]. Assuming the individual measurements are uncorrelated and random, the uncertainty in the calculated quantity is determined as Equ. 7.1.

Equ. 7.1

$$U_y = \sqrt{\sum_i \left(\frac{\partial Y}{\partial X_i} \right)^2 \cdot U_{X_i}^2}$$

where U represents the uncertainty of the variable.

7.1 Detailed Analysis for Summed Energies for One Store

One store was studied in detail, store 1, to determine the uncertainties of the energy quantities used to calculate the performance indicators. This involved creating a table with all the measured data. The test lasted 193 h and the data were stored every 0.025 h, resulting in a table with 7721 rows. The systematic and random uncertainties were then calculated using this data.

The uncertainties used for the measured data are those that were defined for the test method: ±2% for the volume flows and ±0.05°C for temperature differences. It was assumed that there was no uncertainty in the calculation of the density or heat capacity of the fluid for the various data points. Note that when using water/glycol mixtures, the uncertainty in the properties of the fluid are not negligible, but this was not taken into account in this study. The uncertainties were arbitrarily split into the two components, systematic and random uncertainty in the ratio 3 to 4. Assuming that these two components act independently, the combined uncertainty is the square root of the sum of the squares as in Equ. 7.2 (Equ. 4.25 of An Introduction to Error Analysis by Taylor 1982).

Equ. 7.2

$$U = \sqrt{U_{ran}^2 + U_{sys}^2}$$

Table 7.1 shows the resulting values using the defined uncertainties and the chosen ratio. It should be stressed that the division between systematic and random components was strictly arbitrary and other values would have been equally valid. However, based on previous experience the systematic uncertainties should be possible to meet if not better.

Table 7.1. The systematic and random uncertainties used in the study. The uncertainties for the temperature difference were absolute values whereas those for the mass flows were relative.

	Systematic Uncertainty	**Random Uncertainty**
Mass Flow [kg/h]	±1.2%	±1.6%
Temperature Difference [°C]	±0.03°C	±0.04°C

7.1.1 Systematic Errors

The systematic errors were calculated by applying correction terms to the equation calculating the heat transfer so that the uncertainties defined in Table 7.1 were added/multiplied to the base value as in Equ. 7.3 and Equ. 7.4. The same method was applied to all circuits, and the relevant energies were calculated as previously, by time integrating the heat transfer rates for each time step.

Equ. 7.3 $$\dot{Q}_{b,sys,dT} = Cp_s \cdot \dot{m}_b \cdot (dT_b + 0.03) \cdot \left[0.000277778 \cdot \frac{h}{s} \right]$$

Equ. 7.4 $$\dot{Q}_{b,sys,mdot} = Cp_s \cdot \dot{m}_b \cdot 1.012 \cdot dT_b \cdot \left[0.000277778 \cdot \frac{h}{s} \right]$$

The resulting energies were compared to the base values (no uncertainty) to calculate the uncertainty for the summed energy using Equ. 7.5 and Equ. 7.6, and similar equations for the other circuits.

Equ. 7.5 $$U_{b,sys,mdot} = \int (\dot{Q}_{b,sys,mdot})\, dt - \int (\dot{Q}_b)\, dt$$

Equ. 7.6 $$U_{b,sys,dT} = \int (\dot{Q}_{b,sys,dT})\, dt - \int (\dot{Q}_b)\, dt$$

7.1.2 Calculation of Combined Uncertainties for Summed Energies

The random errors were calculated using a set of equations that implement Equ. 7.1 and calculated for the whole time period of the test sequence to give $U_{b,ran}$ for the boiler circuit and similarly for the other loops. The calculation of the combined uncertainty assumes that all the uncertainties are independent. It is calculated using Equ. 7.7 and similar equations for the other circuits.

Equ. 7.7 $$U_{Qb} = \sqrt{U_{b,sys,dT}^{\,2} + U_{b,sys,mdot}^{\,2} + U_{b,ran}^{\,2}}$$

Equ. 7.8 $$U_{Qloss} = \sqrt{U_{Qb}^{\,2} + U_{Qc}^{\,2} + U_{Qhs}^{\,2} + U_{Qdhw}^{\,2} + U_{Qs}^{\,2}}$$

For the whole test sequence, the energy balance for the store (Equ. 4.4), the only quantity not measured directly is Q_{loss}, because at the end of the test the internal energy (Q_s) of the store can be determined when the store is mixed or conditioned to 20°C. The uncertainty for this value is thus given by Equ. 7.8.

The same equations can be used to determine the uncertainties at different time points within the test sequence.

7.2 Calculation of Uncertainties for the Performance Indicators

7.2.1 $dQ_{s,end}$

This was calculated using the uncertainty propagation in EES and the equations defined in section 4.1.2. The following uncertainties were used:

- As described in the previous sections for the summed energies for the secondary conditioning period (incl. Q_{loss}).
- V_s ±3%.
- $T_{s,end}$ ±0.1°C.
- $Q_{DHW,fd}$ (final discharge at end of core phase) ±1.2%.

7.2.2 $UA_{s,loss}$

The relative uncertainty for the heat loss coefficient was assumed to be the same as that for the total heat losses for the test sequence. The uncertainty for the time integrated temperature difference ($dTt_{s,loss}$) is completely dependent on the heat losses and is thus not independent.

7.2.3 η_{store}

This was calculated using the uncertainty propagation in EES. The uncertainties for the summed energies were calculated as described in the previous sections, and for $dQ_{s,end}$ as in section 7.2.1.

7.2.4 F_{SAV}, $Q_{cap,cg}$ and $Q_{cap,DHW}$

These were calculated using the uncertainty propagation in EES and the equations defined in section 4.1.2. The uncertainties for the summed energies were calculated as described in the previous sections.

7.2.5 $E_{aux,y}$

Eaux,y is only dependent on the values for the auxiliary heating and loads during the core phase. The uncertainties were calculated using uncertainty propagation in EES based on an uncertainty of 1.23% for heat transfer energies and 0.7% for electricity.

7.2.6 Extrapolation of Results to Other Stores

The results obtained for store 1 were analysed. Based on these results, the uncertainties for all quantities used in the calculation of the performance indicators were estimated. This approach was used to save time and was justified by the consistency of the uncertainties determined for store 1.

7.3 Results

7.3.1 Detailed Analysis for Store 1

The uncertainties for the energies for the four circuits for the test sequence were calculated as described in section 7.1. This was done for the whole test sequence (Table 7.2), the secondary conditioning phase (Table 7.3) and the core phase (Table 7.4). The results show a striking consistency for the relative errors of all circuits, and even the uncertainty for the heat losses are relatively similar, those for the shorter secondary conditioning section being higher. The uncertainties for the systematic errors dominate, especially that of the volume flow measurements. All relative errors for the circuits are close to the systematic error for the volume flow of 1.2%, the highest being only 1.24%. It is thus obvious, as is usually the case, that it is very important to reduce the systematic errors as much as possible, especially those for the volume flow. Those for the temperature difference are less critical. The random uncertainties are of even less importance, as many measurements are involved.

Table 7.2. Calculated uncertainties for the four circuits and that derived for Q_{loss} for the whole test sequence. Q_{loss} was calculated from the energy balance at the end of the test sequence.

	Q_c [kWh]	Q_b [kWh]	Q_{dhw} [kWh]	Q_{hs} [kWh]	Q_{loss} [kWh]
Best value	85.99	293.70	84.68	278.10	15.12
$U_{sys,dT}$	0.19	0.50	0.08	0.40	
$U_{sys,mdot}$	1.03	3.60	1.02	3.40	
U_{ran}	0.04	0.16	0.12	0.07	
U_{total}	1.05	3.64	1.03	3.42	5.21
Rel. Unc.	1.22%	1.24%	1.22%	1.23%	34.44%

Table 7.3. Calculated uncertainties for the four circuits and that derived for Q_{loss} for the secondary conditioning phase only. Q_{loss} was calculated using the equations for the heat losses.

	Q_c [kWh]	Q_b [kWh]	Q_{dhw} [kWh]	Q_{hs} [kWh]	Q_{loss} [kWh]
Best value	22.47	76.96	20.76	58.95	3.169
$U_{sys,dT}$	0.04	0.10	0.02	0.08	
$U_{sys,mdot}$	0.27	0.92	0.25	0.71	
U_{ran}	0.02	0.09	0.06	0.03	
U_{total}	0.27	0.93	0.26	0.71	1.23
Rel. Unc.	1.22%	1.21%	1.24%	1.21%	38.90%

Table 7.4. Calculated uncertainties for the four circuits and that derived for Q_{loss} for only the core phase. Q_{loss} was calculated as the difference between the values for the end of the test sequence and the end of the secondary conditioning.

	Q_c [kWh]	Q_b [kWh]	Q_{dhw} [kWh]	Q_{hs} [kWh]	Q_{loss} [kWh]
Best value	63.52	216.74	63.92	219.15	11.95
$U_{sys,dT}$	0.16	0.30	0.04	0.30	
$U_{sys,mdot}$	0.76	2.60	0.77	2.63	
U_{ran}	0.03	0.14	0.09	0.07	
U_{total}	0.78	2.62	0.77	2.65	3.88
Rel. Unc.	1.23%	1.21%	1.21%	1.21%	32.50%

These results were then used to determine the uncertainties for the performance indicators as described in section 7.2. The results can be seen in Table 7.5.

7.3.2 Extrapolation of Results to Other Stores

Based on the results for store 1 it was decided to use constant values in the calculation of the uncertainties for the performance indicators of the other stores. This was justified by the uniformity of the uncertainties for the summed energies and by the fact that the predominant uncertainty was that of the systematic uncertainty for the volume, a value that was chosen arbitrarily. The uncertainty for all the summed energies was fixed to 1.23% (relative) for these calculations.

The relatively low uncertainty for store 2 is due to the fact that the auxiliary energy source is electricity, for which an uncertainty of 0.7% was assumed.

Table 7.5. Uncertainties for the performance indicators calculated for the ten stores.

Store	**Volume [m^3]**	**F_{SAV} [%]**	**$E_{aux,y}$ [kWh]**	**η_{store} [%]**	**$UA_{s,loss}$ [W/K]**	**$dQ_{s,end}$ [kWh]**
1	0.773	22.6±1.2	15702±1.6%	95.9±1.3	-2.59±0.88	1.1±1.4
2	0.773	34.5±0.8	15599±1.3%	95.9±1.2	-2.78±0.94	-0.2±1.2
3	0.476	14.3±0.7	17489±0.9%	93.2±0.7	-2.13±0.72	-1.4±1.2
4	0.763	19.6±1.3	16337±1.6%	94.5±1.3	-3.32±1.13	-1.3±1.7
5	0.763	22.3±1.2	15778±1.6%	97.3±1.3	-1.57±0.53	-0.7±1.2
6	0.763	22.0±1.2	15843±1.6%	97.2±1.3	-1.57±0.53	-0.9±1.2
7	1.513	23.0±1.2	15696±1.6%	96.0±1.3	-2.36±0.80	-0.6±1.6
8	2.263	20.8±1.2	16194±1.6%	94.8±1.3	-3.13±1.07	5.5±2.0
9	1.263	11.0±1.4	18180±1.6%	91.6±1.1	-3.68±1.24	-0.1±3.7
10	2.013	12.0±1.4	18117±1.6%	91.7±1.2	-3.66±1.24	-1.7±3.6

8 Discussion and Conclusions

The work presented here should be judged as the start of a process for developing a new test method. The aims and specifications outlined in section 2 are quite comprehensive and not all of them have been met. This is mainly due to a time restraint within the project. A set of performance indicators has been proposed and the results show that they give a reasonable measure of the store. However, the two indicators for store losses have relatively large uncertainties and it is therefore not easy to rank or compare the losses from stores with any great certainty. A separate and specific test sequence, such as the HL sequence of the full CEN method, would be required in order to derive a more accurate measure of the losses. This statement is valid for both the direct characterisation and annual calculation. The results obtained in this work are quite good, but this due to the fact that the results are based purely on simulations and have no influence from measurement uncertainties.

The fractional energy savings are derived reasonably well from Combitest, although the absolute values are too high. In order to get results from Combitest that are representative for the year, there are two options: using a correction factor, or changing the conditions of the test sequence. The second is probably preferable, as this will also affect the other performance indicators in such a way that they too become more representative of annual values. In addition, larger stores will probably require a longer test sequence in order to deal with the greater stored energies. This is especially true of stores charged from wood boilers, as there can be large amount of stored auxiliary energy as well as solar from one season to another. The ranking of the stores is the same for both the Combitest results and annual simulation, apart from two stores that are interchanged. Again this is without the influence of measurement uncertainties.

The alternative performance indicator for overall system performance proposed in Task 26, $E_{aux,y}$, also shows consistent results. There is a clear linear relationship between the performance indicator and the simulated auxiliary energy use for the equivalent system over a whole year. However, the value is not the same as the simulated annual value. Moreover the difference is dependent on the value of $E_{aux,y}$. Again a correction factor could be applied to $E_{aux,y}$, in order to make it more accurately predict the annual auxiliary energy use.

The two indicators for heat losses, $UA_{s,loss}$ and η_{store}, have relatively large uncertainties for them and cannot be used for an accurate comparison of different stores heat losses. In order to get an accurate value an extra test specifically designed to determine the heat loss coefficient would be required. The uncertainty in fractional energy savings is obviously dependent on the sensor uncertainties (as are all the other derived indicators). It is in the range of 1-2%-points (4-20% relative).

One of the performance indicators, the time between charges (t_{cgint}), was not successfully adopted for wood boilers as the charging strategy used for them allowed charges only at fixed times. Another charging strategy (not realistic) or some other measure is thus required.

The incorporation of a DHW comfort test into the test sequence appears to work well, although it would be dependent on the final details of the test. A significant discharge is required in the secondary conditioning in order to condition the store quickly and this can just as easily be achieved by a comfort test as by any other discharge.

The annual calculation part, utilising parameter identification and long-term simulation, was not studied in depth due to time constraints. The results for the one store tested, are however, very promising.

There is also the issue of the setting of the auxiliary controller thermostats that has not been fully addressed in this work. This affects the results in two ways. The first is that for solar heating systems it affects how much solar can be utilised. Secondly, for all systems, it can mean that the set loads are not met. In this work, no detailed analysis of possible compensation methods has been made. A simple method for compensation was applied to the annual simulations. This showed that, for the settings used, the compensation would alter the calculated fractional savings by up to 3% (relative) for the 10 stores tested.

Only 10 store variations have been tested here. A wider range needs to be tested before any real conclusions can be drawn. In addition the results are based purely on simulation data and the results are naturally better than those that would be achieved with measurements. However, these initial results show that the method is promising.

The specification for the validation of the test stand appears to be a bit stringent, according to the simple uncertainty analysis carried out for the performance indicators.

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