

Altener program: SOLAR COMBISYSTEMS

WORKPACKAGE 6 MONITORING RESULTS FOR 3 FRENCH PLANTS

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Symbol list

Symbol	Definition	Unit
A	area	m ²
C	consumption	kWh
H	mean heat loss coefficient	W/K
I	solar irradiation	kWh/m ² .j
N _{jm}	number of days in a month	-
Q	energy quantity, load, loss	kWh
Q _c	energy delivered by the solar collector	kWh
Q _h	space heating load	kWh
Q _i	internal gains	kWh
Q _{inj,h}	energy injected in the space heating loop	kWh
Q _w	domestic Hot Water load	kWh
θ	temperature	°C
θ _w	cold water temperature	°C
θ _e	outdoor temperature	°C
θ _i	inside temperature	°C
η	efficiency	%
X	Ration irradiation/reference consumption	-
W	electric consumption	kWh
Δt	running time	H
Suffixes		
aux	auxiliary	
bur	boiler	
c	solar collector	
conv	conventional	
e	outdoor	
el	electrical	
ext	extended (thermal and electrical)	
h	space heating	
i	internal	
loss	losses	
m	monthly	
ref	reference	
sav	saved	
sol	solar	
st	stored	
therm	thermal	
w	Domestic Hot Water	
*	used when a definition is slightly modified	
Fonts		
normal	calculated values	
bold	identified or estimated values	
<i>italic</i>	measured values	

Annual and monthly values :

In general, energy balances can be calculated on a yearly or monthly period, with same formula. If the annual formula are ambiguous, the symbol **S** is placed before the concerned figure.

Introduction

Three typical French solar combisystems have been monitored according the guidelines elaborated in the framework of the Altener project : SOLAR COMBISYSTEMS [1]

1. Presentation of the monitored plants

The three houses are new buildings, located in east and south of France, equipped with the most common French combisystems called "Direct Solar Floor", documented in 21 of the 23 presented French plants. This system is sytem #3a in the Design Handbook of task 26.

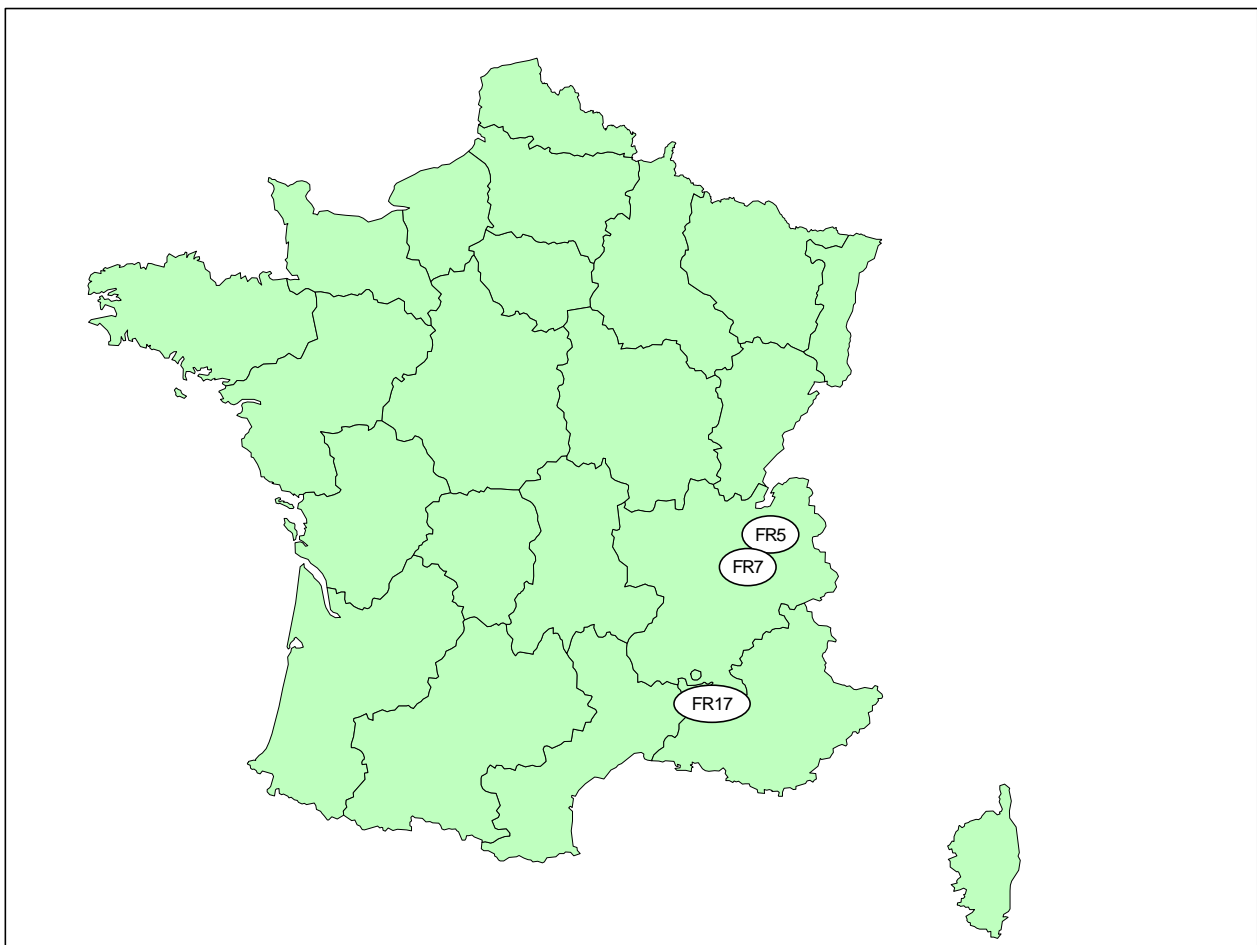


Figure 1 : Location of the monitored plants

The plants are built with factory-made compact technical units, each of them however using a different auxiliary energy : electricity for the first, oil for the second and natural gas for the third. No tank is used for storage of solar energy for space heating : heat delivered by the solar collector is directly injected in a heating floor, and stored in a concrete layer which is slightly thicker than usually.

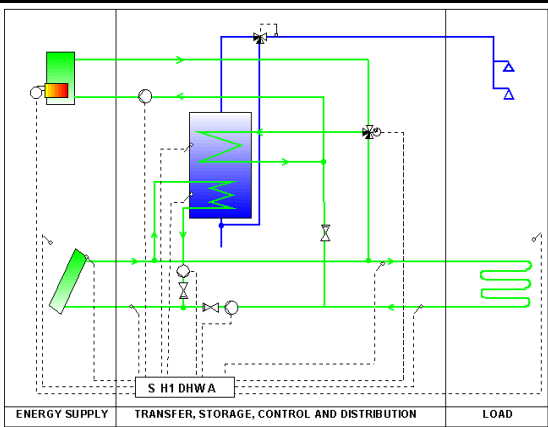
When no solar heat is available, auxiliary energy is provided by a boiler, connected to the heating floor directly, without any heat exchanger. These features allow the collector to work at the lowest possible temperature level, increasing thus its efficiency.

1.1. Plant FR5



Main datas of building :

Total number of inhabitants	4
Total heated area	100 m ²
Design outdoor temperature for space heating system	-17 °C
Design heating degree days (19)	3746 Kd
Total yearly space heating demand	14496 kWh/a
Total yearly DHW demand	3413 kWh/a
Total energy demand (space heating + DHW)	17909 kWh/a
Latitude	45.4 °
Situation	74250 BOGEVE



Main datas of energy system :

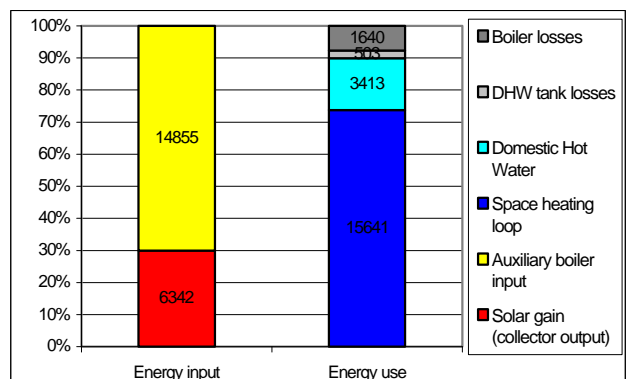
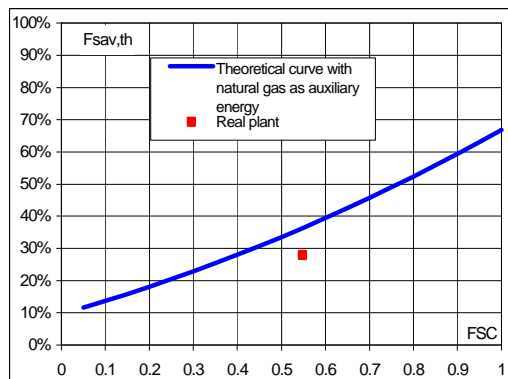
System No. of task 26 brochure	#3a
Gross collector area	15.7 m ²
Net collector area	13.9 m ²
Heat storage volume	none
DHW storage volume	0.50 m ³
Nominal power of auxiliary heater	9.6 kW
Auxiliary energy	electricity
Type of space heating system	heating floor
Total system cost per m ² collector	570 €/m ²
<i>self installation</i>	
<i>pipework missing</i>	



Main energy datas of solar combisystem :

simulation

Solar gain	6342 kWh/a
Energy savings	5786 kWh/a
Energy savings per m ²	369 kWh/m ² .a
Fractional energy savings	28 %
FSC	0.55
Specific space heating load per m ²	923 kWh/m ²
Specific DHW load per m ²	217 kWh/m ²
Specific total load per m ²	1141 kWh/m ²
Solar conversion factor	27 %
System efficiency (without boiler)	92 %
System efficiency (with boiler)	84 %

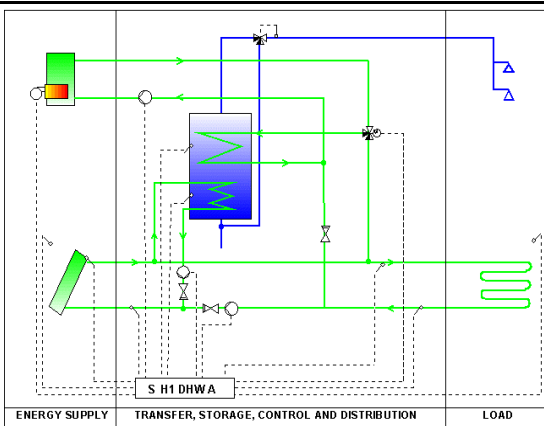


1.2. Plant FR7



Main datas of building :

Total number of inhabitants	1
Total heated area	190 m ²
Design outdoor temperature for space heating system	-11 °C
Design heating degree days (19)	3033 Kd
Total yearly space heating demand	18611 kWh/a
Total yearly DHW demand	1664 kWh/a
Total energy demand (space heating + DHW)	20276 kWh/a
Latitude	45.4 °
Situation	73230 ST ALBAN



Main datas of energy system :

System No. of task 26 brochure	#3a
Gross collector area	20.4 m ²
Net collector area	16.7 m ²
Heat storage volume	none
DHW storage volume	0.33 m ³
Nominal power of auxiliary heater	25.0 kW
Auxiliary energy	oil
Type of space heating system	heating floor
Total system cost per m ² collector	492 €/m ²

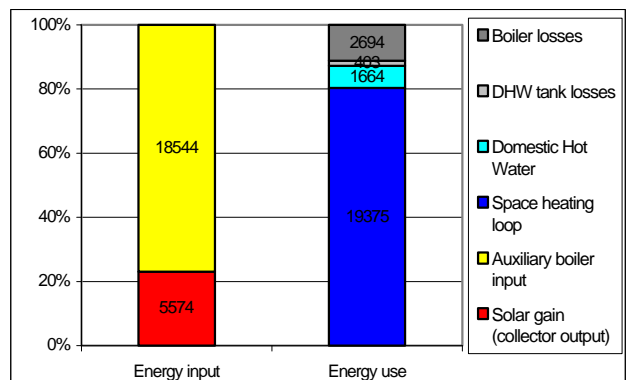
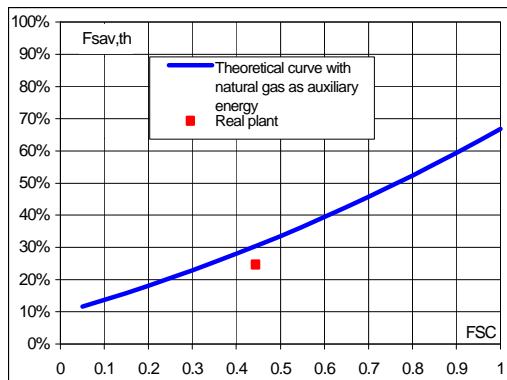
pipework missing



Main energy datas of solar combisystem :

simulation

Solar gain	5574 kWh/a
Energy savings	6070 kWh/a
Energy savings per m ²	297 kWh/m ² .a
Fractional energy savings	25 %
FSC	0.44
Specific space heating load per m ²	912 kWh/m ²
Specific DHW load per m ²	82 kWh/m ²
Specific total load per m ²	994 kWh/m ²
Solar conversion factor	22 %
System efficiency (without boiler)	95 %
System efficiency (with boiler)	84 %

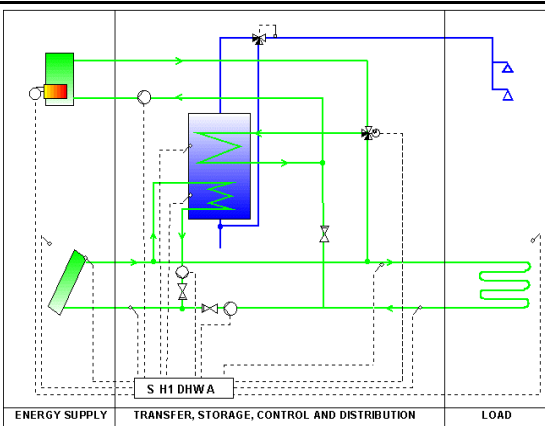


1.3. Plant FR17



Main datas of building :

Total number of inhabitants	4
Total heated area	150 m ²
Design outdoor temperature for space heating system	-6 °C
Design heating degree days (19)	2083 Kd
Total yearly space heating demand	10085 kWh/a
Total yearly DHW demand	3087 kWh/a
Total energy demand (space heating + DHW)	13172 kWh/a
Latitude	44.1 °
Situation	84140 MONTFAVET



Main datas of energy system :

System No. of task 26 brochure	#3a
Gross collector area	19.3 m ²
Net collector area	16.7 m ²
Heat storage volume	none
DHW storage volume	0.33 m ³
Nominal power of auxiliary heater	24.0 kW
Auxiliary energy	natural gas
Type of space heating system	heating floor
Total system cost per m ² collector	573 €/m ²

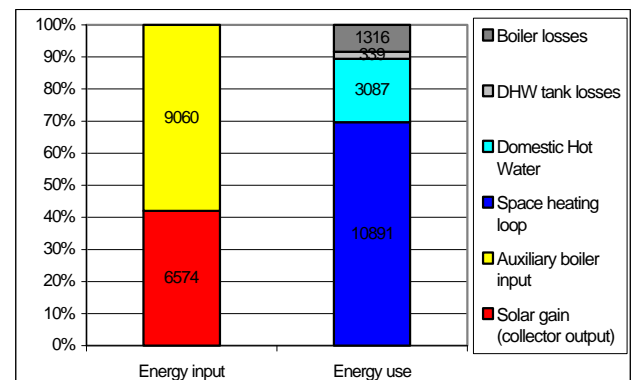
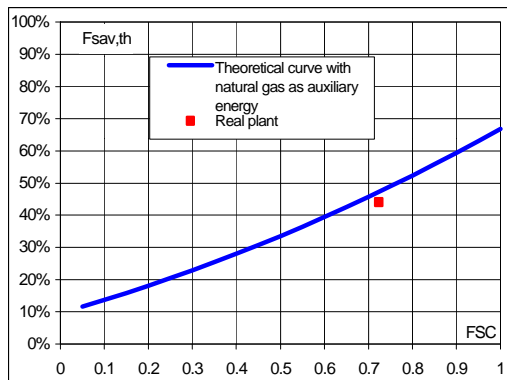
self installation of the collector
self installation of the heating floor



Main energy datas of solar combisystem :

simulation

Solar gain	6574 kWh/a
Energy savings	7169 kWh/a
Energy savings per m ²	371 kWh/m ² .a
Fractional energy savings	44 %
FSC	0.72
Specific space heating load per m ²	523 kWh/m ²
Specific DHW load per m ²	160 kWh/m ²
Specific total load per m ²	683 kWh/m ²
Solar conversion factor	25 %
System efficiency (without boiler)	92 %
System efficiency (with boiler)	84 %



2. Monitoring equipment

Table 1 gives the list of measured data, located on figure 2 :

Symbol	Meaning	Unit	Comments
E, G, O	auxiliary consumption	kWh	E : electricity meter G : gas meter O : oil meter
I	solar irradiation on the solar collector	kWh/m ²	Calibrated PV cell
Q_w^*	DHW load	kWh	F1, T13, T12
$Q_{inj,h,sol}$	solar energy injected in the space heating loop	kWh	F3, T6, T7, solar pump working
$Q_{inj,h,aux}$	auxiliary energy injected in the space heating loop	kWh	F3, T6, T7, auxiliary pump working
$Q_{inj,h}$	energy injected in the space heating loop	kWh	F3, T6, T7
$Q_{inj,w,sol}$	solar energy injected in the DHW tank	kWh	(F2, T14, T5) – (F3, T6, T7)
$Q_{inj,w,aux}$	Auxiliary energy injected in the DHW tank	kWh	F4, T16, T15
W_{el}	parasitic electricity consumption	kWh	
Q_c	energy delivered by the solar collector	kWh	F2, T14, T5
θ_i	inside temperature	°C	T2
θ_e	outdoor temperature	°C	T1
Δt	running time of pumps	h	

Table 1 : measured data

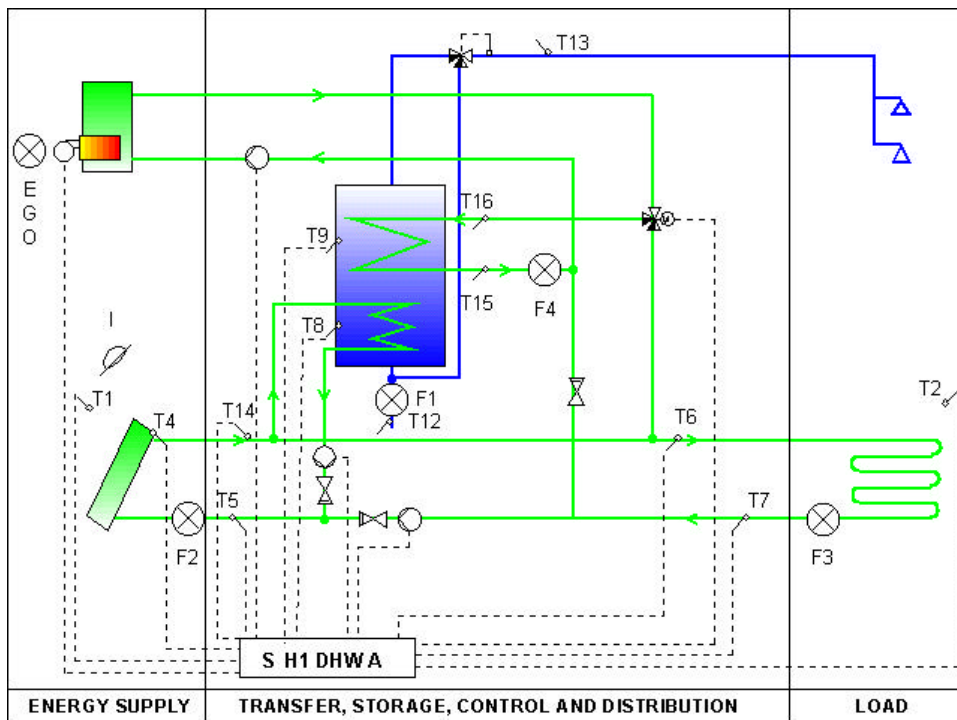


Figure 2 : Location of the sensors and meters

All temperature sensors and all flow-meters are connected to a data-logger integrated in the control device. Energy calculations are made every thirty seconds, and several meters are incremented at each timestep. Some **additional measurements** are made by inhabitants with remote meters, and sent once a month to ASDER office :

- solar irradiation on the collector area with a calibrated PV cell located in the collector area
- used auxiliary energy (gas-, electric- or oil-meter)
- parasitic electricity

After some months needed to learn how to do it, it works quite well, because inhabitants are strongly motivated and willing to know how their plant works.

3. Estimation of the space heating load

A particularity of system #3a is that the floor is used as space heating storage. That means that more solar energy than strictly needed with regard to the space heating load, is injected in the floor when available. This is allowed by a two level set-point room temperature : low level (typically 19 °C) is chosen when auxiliary energy is injected in the floor, and a higher level (typically 4 °C more than the first setpoint temperature, that is 23 °C) is used when solar energy is injected in the floor.

This feature prevents to consider energy injected in the space heating loop as the space heating load. To calculate this load, it is necessary to identify the real thermal characteristics of the house.

3.1. Identification of the real thermal coefficients of the house

The approach presented hereunder is based on the French Thermal Regulation 2000 [2]. Energy balances are calculated on a monthly basis.

For a fully heated month, the space heating load Q_h is defined according to an equivalent inside temperature θ_{ieq} and the outdoor temperature θ_e with the following formula :

$$Q_h = H \cdot (\theta_{ieq} - \theta_e) \cdot 0,024 \cdot N_{jm} - \eta \cdot (Q_s + Q_i) \quad (\text{kWh}) \quad (1)$$

where Q_s : solar gains (kWh)
 Q_i : internal gains (kWh)
 H : mean heat loss coefficient (W/K)
 η : free gains utilization ratio
 N_{jm} : number of days in the month

Solar gains can be calculated from the equivalent South Area A_{ss} (fictitious vertical glass area, South oriented, that provides the same solar gains as the real windows), from the mean south vertical irradiation E and from the number of days N_{jm} with the following formula :

$$Q_s = A_{ss} \cdot E \cdot N_{jm} \quad (2)$$

Internal gains are estimated from the heated area A_{bat} and from a coefficient I_i (daily internal gains in kWh per m² of heated area) with the following formula:

$$Q_i = I_i \cdot A_{bat} \cdot N_{jm} \quad (3)$$

Equation (1) shows that the 3 characteristic parameters of the house \mathbf{H} , \mathbf{A}_{ss} and \mathbf{I}_i are needed to calculate the theoretical space heating load of the house.

A method to identify these parameters is presented hereunder.

With a heatmeter, the energy injected in the space heating loop $Q_{inj,h}$ can be measured (*If space heating is provided with two different loops, one for the solar part and the second for the auxiliary part, $Q_{inj,h}$ is the sum of both corresponding energy quantities*).

This energy $Q_{inj,h}$ is needed as complement of the free gains (passive solar gains and internal gains) to compensate the space heating losses. The observed inside temperature, and the real degrees-hours DH_{real} calculated from this temperature, are the result of the contribution of these three energy supplies.

It comes then :

$$\mathbf{H}^* \cdot DH_{real} = Q_{inj,h} + Q_s + Q_i \quad (4)$$

where Q_s : passive solar gains (kWh)
 Q_i : internal gains (kWh)
 DH_{real} : thousands of degrees-hours
 \mathbf{H}^* : mean heat loss coefficient taking into account the heat losses of the space heating loop

As the energy injected in the space heating loop $Q_{inj,h}$ integrates the heat losses at the back of the hear emitters and the heat losses of the space heating loop in the downstream side of the heatmeter, the coefficient \mathbf{H}^* , obtained with the identification method, also takes into account the heat losses at the back of the heat emitters and the heat losses of the space heating loop. \mathbf{H}^* is therefore slightly greater than the real heat loss coefficient \mathbf{H} . This must be taken into account when the space heating consumption will be calculated, and these losses shall not be added twice.

For a month, the energy balance is :

$$Q_{inj,h} = \mathbf{H}^* \cdot DH_{real} - (\mathbf{A}_{ss} \cdot E + \mathbf{I}_i \cdot A_{bat}) \cdot N_{jm} \quad (5)$$

The first step in the calculation of the space heating load consists in finding the real value of the 3 characteristic parameters of the house (\mathbf{H}^* , \mathbf{A}_{ss} and \mathbf{I}_i), that will minimize the gap between the calculated energy injected in the space heating loop (equation 5) and the measured injected energy $Q_{inj,h}$. This can be done by minimizing the mean quadratic gap between both sets of monthly data. In this fitting, N_{jm} represents the number of days in a month, DH_{real} represents the monthly value for degrees-days, derived from the real inside temperature, E represents the monthly value for the mean South vertical irradiation, measured on the site or derived from data of the nearest weather station. For this calculation, the first and last months of the heating season, that are not full, are not taken into account.

Theoretically, the three parameters \mathbf{H}^* , \mathbf{A}_{ss} and \mathbf{I}_i should be identified, because they reflect all together the real building, the behaviour of the inhabitants, and the household appliances level. However, this approach has been followed in the project Thermie 75 DSFIA [3]. Nevertheless, it is a little perilous to identify 3 parameters from data including only 5 to 7 pairs of monthly data.

Therefore a simpler approach can be used : it consists in 1) calculating the more precisely possible, from the drawing of the house, the equivalent South Area A_{ss} , 2) using the conventional internal gains coefficient for dwellings $I_i = 96 \text{ Wh/j.m}^2$ and 3) identifying only the heat loss coefficient H^* giving the best data fitting. The equivalent South Area A_{ss} can be estimated with conventional methods. In France, for example, the French thermal regulation is used [4].

3.2. Calculation of the space heating load

When the characteristic parameters are determined, the space heating load is given by equation (1) :

η is the free gains utilization ratio. It is a function of the ratio free gains / heat losses (γ), and of the time constant (τ), which characterizes the thermal inertia of the building :

$$\gamma = (Q_s + Q_i) / (H^* \cdot (\theta_{ieq} - \theta_e) \cdot 0,024 \cdot N_{jm}) \quad (6)$$

$$\eta = (\tau + 16) / (\tau + 32) \quad \text{if } \gamma = 1$$

$$\eta = \frac{1 - \gamma^{(1+\tau/16)}}{1 - \gamma^{(2+\tau/16)}} \quad \text{if } \gamma \neq 1 \quad (7)$$

τ is given by :

$$\tau = C_m / H^* \quad (8)$$

with C_m : daily thermal capacity, which depends of the inertia class, given in the following table :

Inertia class	Daily thermal capacity C_m
Very light	80 / 3,6 . A_{bat}
Light	110 / 3,6 . A_{bat}
Average	165 / 3,6 . A_{bat}
Heavy	260 / 3,6 . A_{bat}
Very heavy	370 / 3,6 . A_{bat}

Table 1 : Daily thermal capacity

The inside equivalent θ_{ieq} is the same as the chosen inside set point temperature θ_i , increased with the spatial and time variations $\delta\theta_{vs}$ and $\delta\theta_{vt}$ according to the space heating emitters and to the controller quality [2].

$$\theta_{ieq} = \theta_i + \delta\theta_{vs} + \delta\theta_{vt} \quad (9)$$

For heating floors, the French Thermal regulation [2] gives : $\delta\theta_{vs} = 0 \text{ K}$ and $\delta\theta_{vt} = 0.9 \text{ K}$

4. Results

4.1. Plant FR5

4.1.1. Monthly results

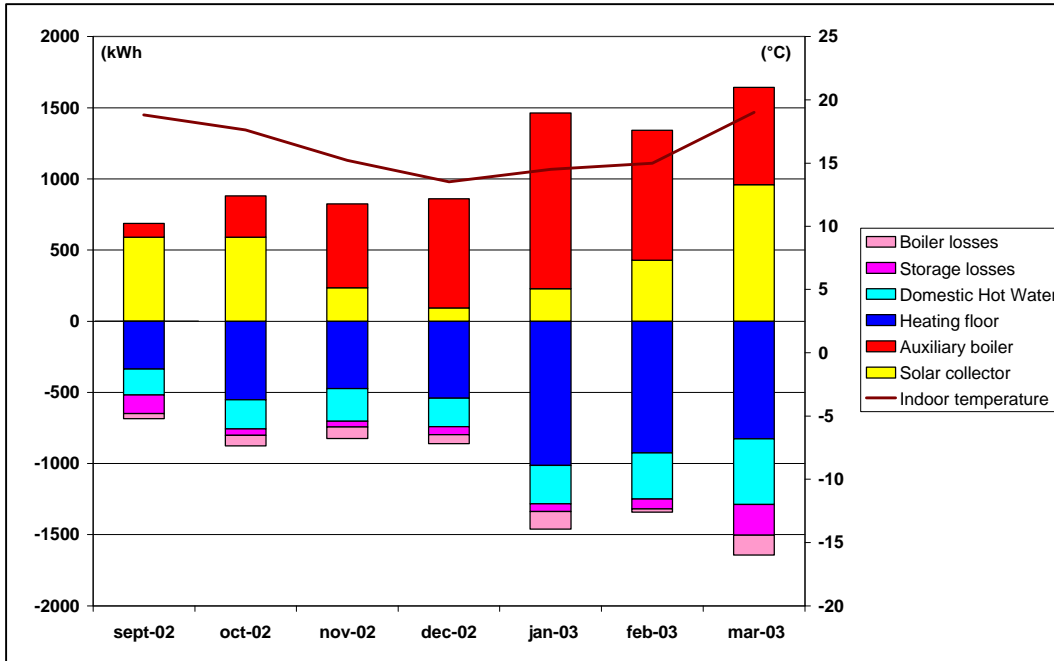


Figure 3 : Monthly results (plant FR5)

Figure 3 shows monthly results. It must be pointed out that the house is not occupied normally, because the owner is still working in it. So the inside air temperature has decreased until 13.5 °C in December.

Figure 4 shows the energy balance during the heating period.

Solar gains represent more than 40 % of energy used.

System efficiency (incl. boiler efficiency) is about 85 %.

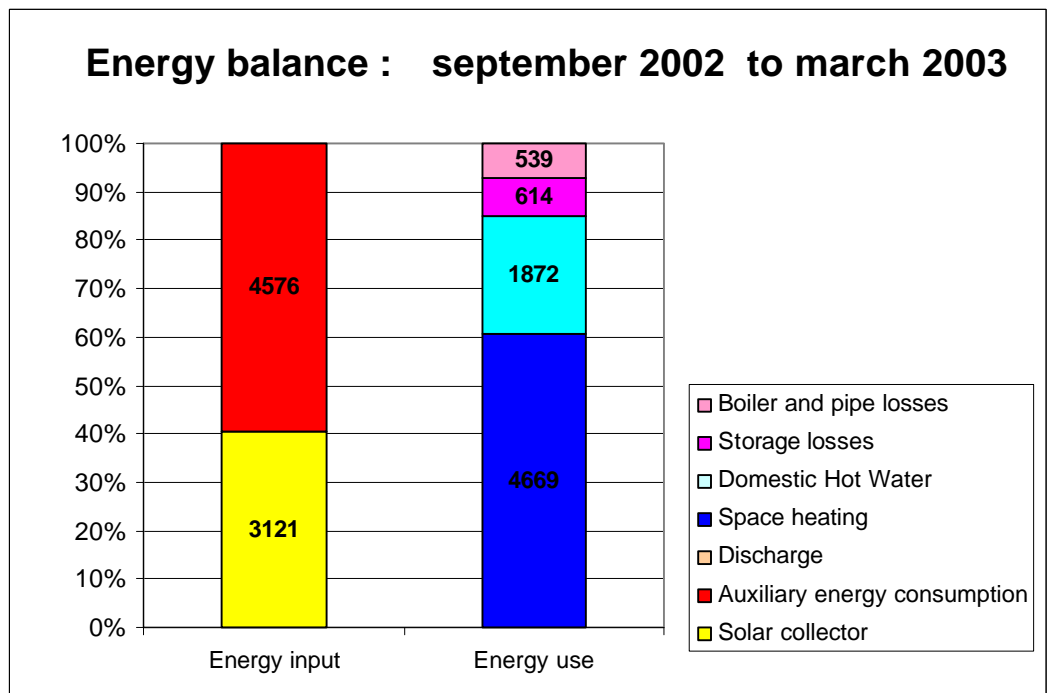


Figure 4 : Energy balance for the heating period (plant FR5)

4.1.2. Extrapolation

Available monthly results have been extrapolated according to the method described in [1]. No identification of the real thermal coefficients of the house has been carried on, because of the low occupancy of the house.

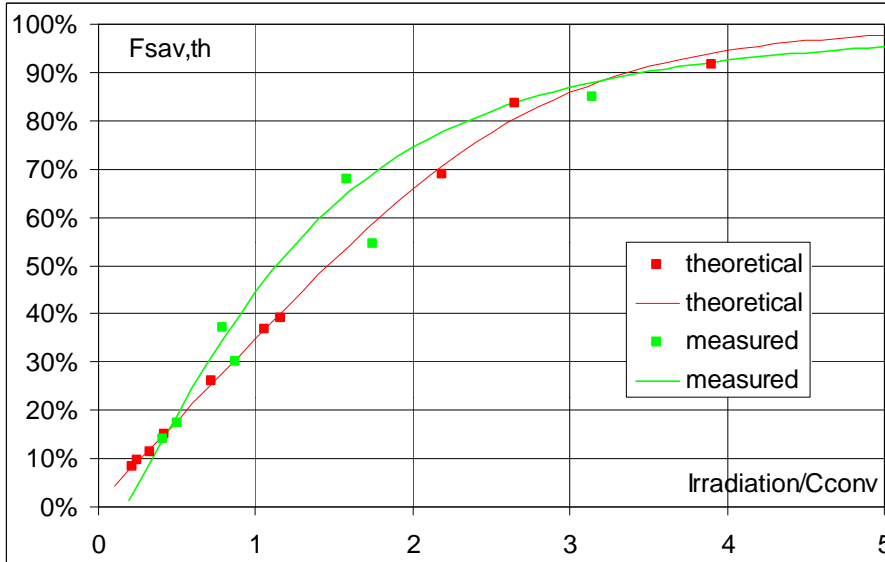


Figure 5 shows the measured characteristic curve of the plant, which is not far from the theoretical one (even a little higher), although the house has not been occupied and heated normally.

Figure 5 : Characteristic curve of the plant FR5

Figure 6 compares monitored results with simulated and theoretical results :

The simulated curve shows the relation between Fractional Energy savings and the Fractional Solar Consumption, for a system using an auxiliary gas boiler.

The theoretical point (red) has been calculated according to [1], with the real auxiliary electric boiler and a theoretical inside air temperature of 19 °C. The measured and extrapolated points (green and blue) differ a lot from the theoretical one because of the much lower real inside temperature.

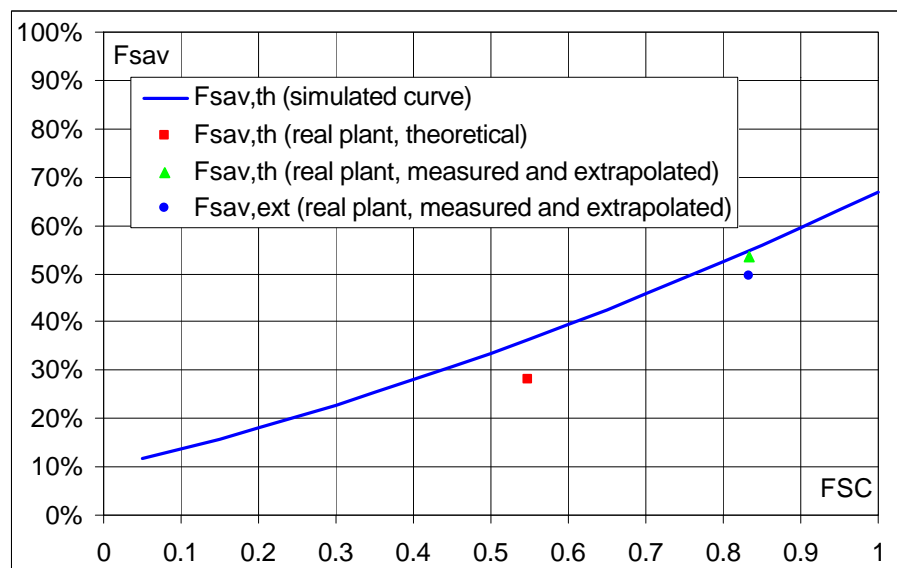


Figure 6: Extrapolation of monthly results (plant FR5)

But it can be noticed that these points are close to the simulated curve, which shows that the system works quite well, even if it is not used as it should be.

The extended fractional solar savings have been simply calculated by estimating a yearly parasitic electricity consumption from the real consumption observed during the 7 months monitoring period. $F_{sav,ext}$ is very close to $F_{sav,th}$, which shows an efficient use of parasitic electricity.

4.2. Plant FR7

4.2.1. Monthly results

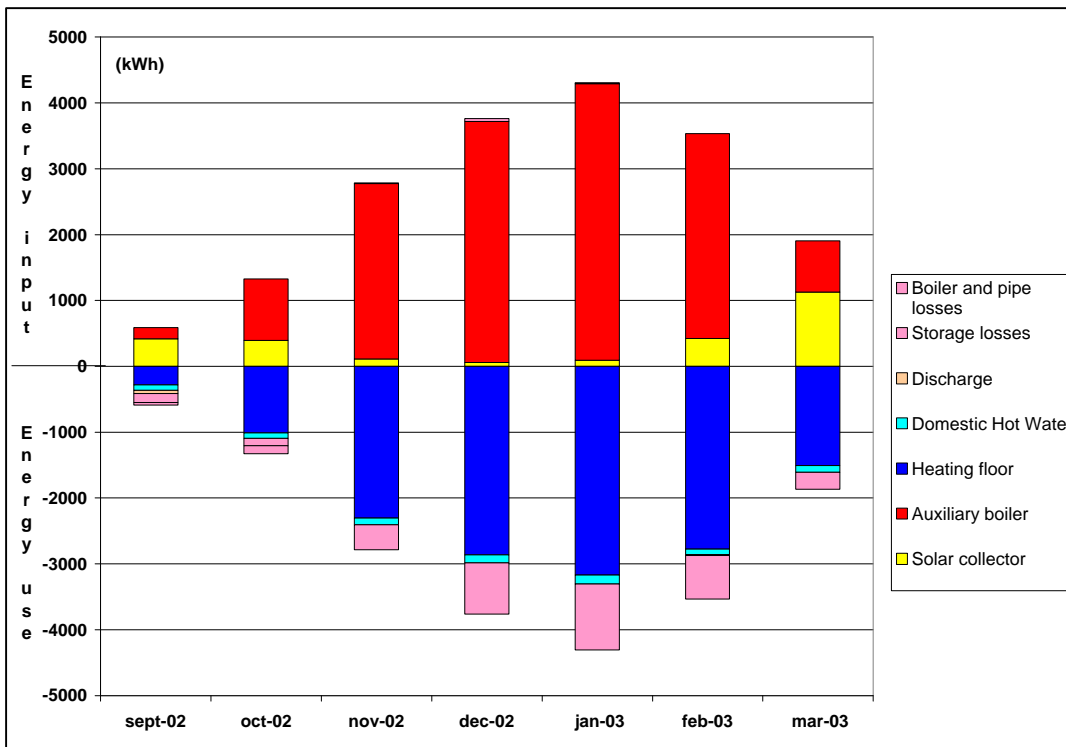


Figure 7 : Monthly results (plant FR7)

Figure 7 shows monthly results. Solar gains are very low. The reason has been pointed out only in February 2003 : the two setpoint inside temperatures were the same, which has decreased dramatically the solar energy injected in the space heating loop. This bad choice has been

corrected in the middle of February : in March, a significant increase of the solar gains can be noticed, compared for example with October 2002.

Figure 8 shows the energy balance during the heating period. The DHW load is very low, due to a one person occupancy of the house. Solar gains represent only less than 20 % of energy used. System efficiency (incl. boiler efficiency) is about 85 %.

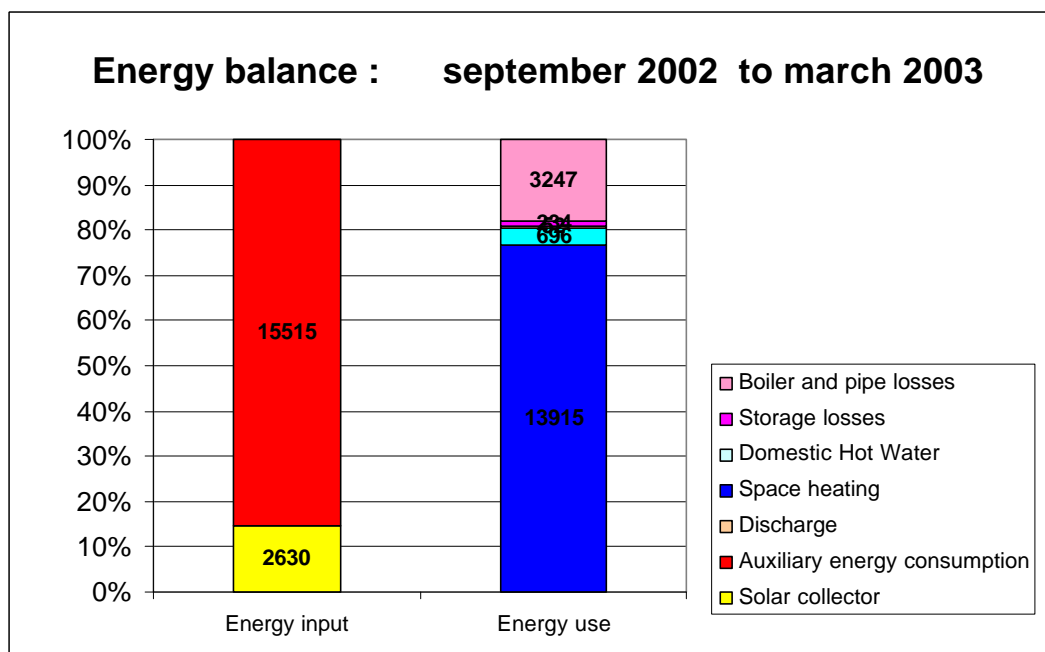


Figure 8 : Energy balance for the heating period (plant FR7)

4.2.2. Extrapolation

The space heating load has been estimated using the method described in chapter 3 (table 2).

	unit	S	O	N	D	J	F	M
energy injected in the floor	kWh	284	1010	2305	2863	3171	2778	1504
space heating load	kWh	376	1043	2229	2992	3554	2962	1372

Table 2 : Estimation of the space heating load

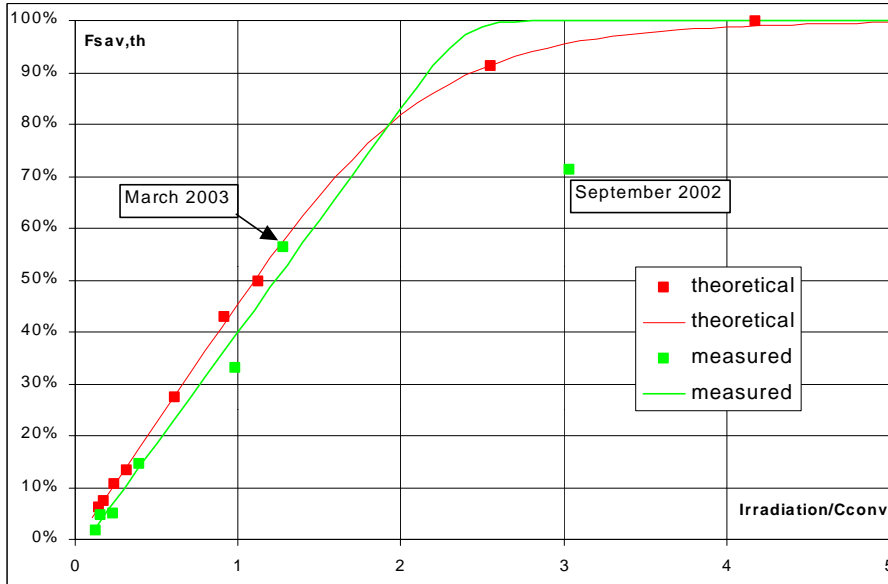


Figure 9 : Characteristic curve of the plant FR7

Available monthly results have been extrapolated according to the method described in [1]. Figure 9 shows the measured characteristic curve of the plant. When calculating it, the September point has been cancelled, because it was too far from a good operation of the system (see above problems related to the inside setpoint temperatures choice).

In March, the system works quite well.

Figure 10 compares monitored results with simulated and theoretical results :

The simulated curve shows the relation between Fractional Energy savings and the Fractional Solar Consumption, for a system using an auxiliary gas boiler.

The theoretical point (red) has been calculated according to [1], with the real auxiliary fuel boiler and a theoretical inside air temperature of 19 °C. The measured and extrapolated point (green) is further from the simulated curve than the theoretical one, because of the bad working of the plant during the winter period.

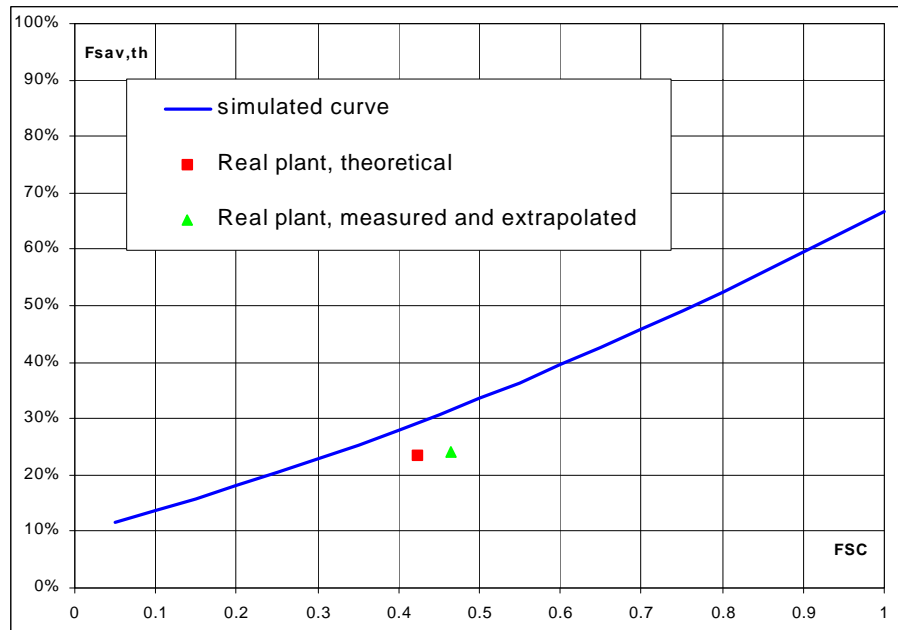


Figure 10 : Extrapolation of monthly results (plant FR7)

The measured and extrapolated point (green) is further from the simulated curve than the theoretical one, because of the bad working of the plant during the winter period.

4.3. Plant FR17

4.3.1. Monthly results

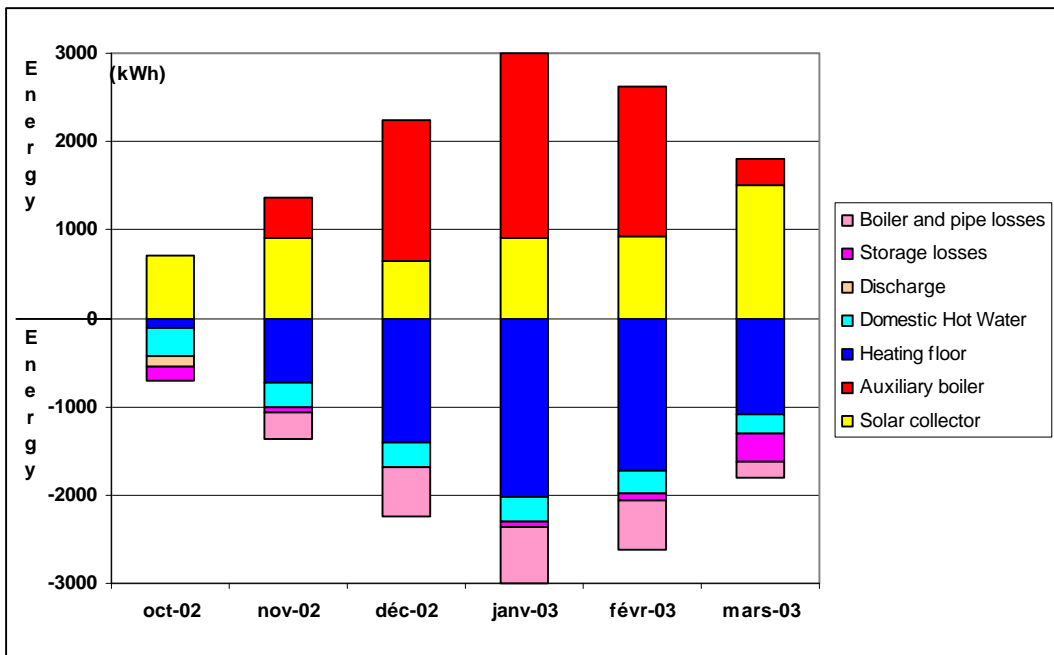


Figure 11 : Monthly results (plant FR17)

Figure 11 shows monthly results. Solar gains are high, even in winter period, because the climate is favourable : high irradiation and outdoor temperature not below 4.5 °C. In March, very few auxiliary energy is needed. In October, no auxiliary energy is needed.

Figure 12 shows the energy balance during the heating period. Solar gains represent only more than 50 % of energy used. System efficiency (incl. boiler efficiency) is about 78 %, that is lower than values for the other plants : DHW tank losses are proportionally higher, because of the higher temperature of DHW reached in the tank due to high solar gains, and also the lower use of the auxiliary boiler, that increases the proportion of boiler losses.

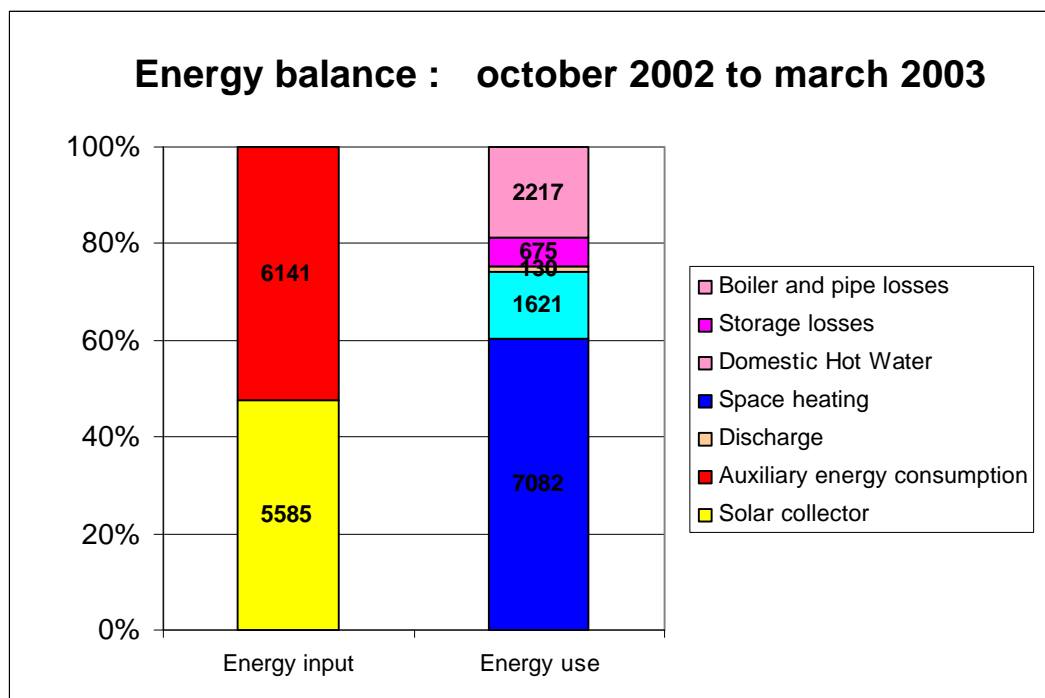


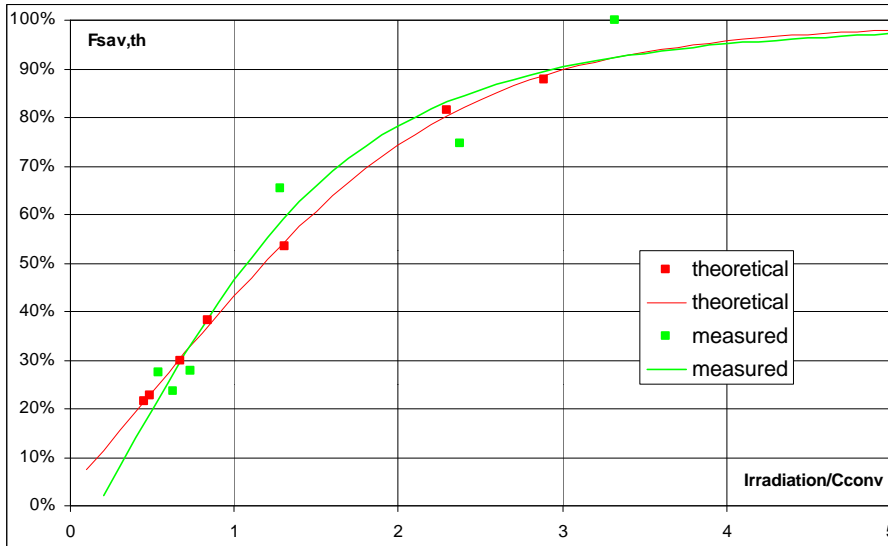
Figure 12 : Energy balance for the heating period (plant FR17)

4.3.2. Extrapolation

The space heating load has been estimated using the method described in chapter 3 (table 3).

	unit	O	N	D	J	F	M
energy injected in the floor	kWh	1010	2305	2863	3171	2778	1504
space heating load	kWh	220	789	1543	2008	1672	689

Table 3 : Estimation of the space heating load



Available monthly results have been extrapolated according to the method described in [1].

Figure 13 shows the measured characteristic curve of the plant.

This curve is higher than the theoretical curve derived from initial dimensioning calculations.

Figure 13 : Characteristic curve of the plant FR17

Figure 14 compares monitored results with simulated and theoretical results :

The simulated curve shows the relation between Fractional Energy savings and the Fractional Solar Consumption, for a system using an auxiliary gas boiler.

The theoretical point (red) has been calculated according to [1], with the real auxiliary gas boiler and a theoretical inside air temperature of 19 °C. Therefore this point is much closer from the simulated curve than for the 2 other plants. The measured and extrapolated points (green and blue) are very close from the simulated curve, which shows that the plant works quite good.

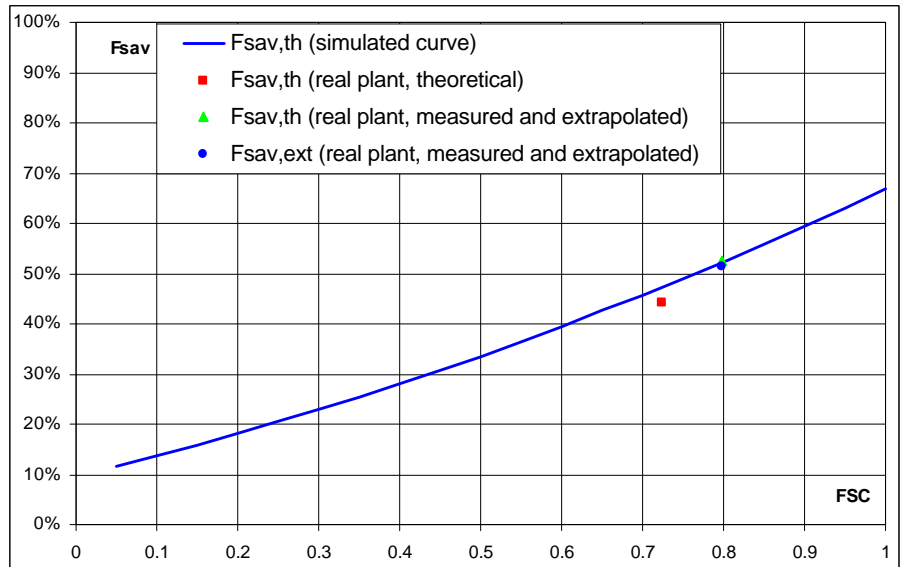


Figure 14 : Extrapolation of monthly results (plant FR17)

5. Conclusion

Main extrapolated results are summarized in table 4 and figure 15.

		FR5	FR7	FR17
Energy savings	kWh/a	5648	5120	6911
Energy savings per m ²	kWh/m ² .a	360	251	358
Fractional energy savings	%	52	24	53
FSC		0.83	0.46	0.80
Specific space heating load per m ²	kWh/m ²	371	797	378
Specific DHW load per m ²	kWh/m ²	205	59	168
Specific total load per m ²	kWh/m ²	577	856	547
Solar conversion factor	%	27	22	25

Table 4 : Main extrapolated results

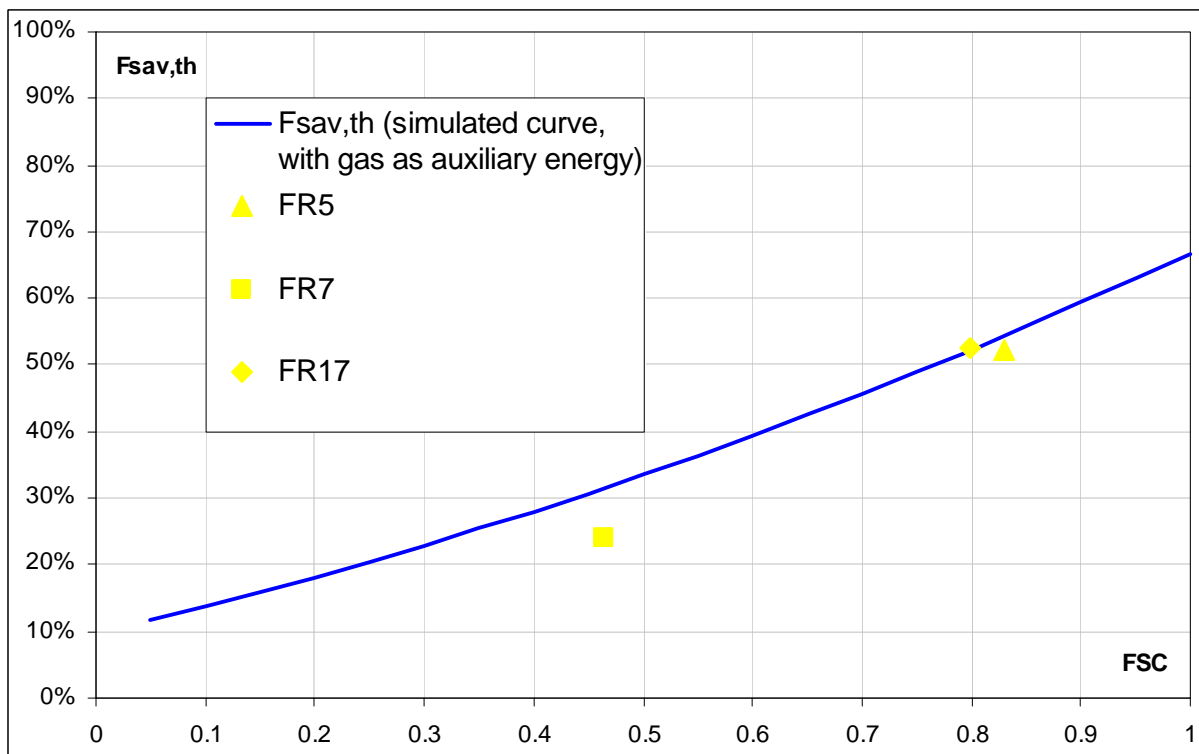


Figure 15 : Extrapolation of monthly results (plant FR17)

Results for the 3 monitored plants are quite good, and close to the theoretical curve. Only for FR7, there is a small gap, due to the auxiliary energy used (oil in the monitored plant and gas for the theoretical curve) and a bad choice for the inside air set-point temperature.

Energy savings per m² and solar conversion factor are lower for FR7 than for other plants, mainly because of the big difference between the DHW specific load and the specific space heating load (ratio 1 to 10 for FR7, about 1 to 2 for FR5 and FR17). For FR7, the collector area is "oversized" during summertime.

6. Bibliography

[1] : LETZ T., Altener program: SOLAR COMBISYSTEMS : WORKPACKAGE 6 : MONITORING PROCEDURE, march 2003, 18 p.

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