On Site Monitoring of a Solar Boiler System: Energy Efficiency and Economy

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ABSTRACT

Active solar heating was a favorite topic after the first energy crisis. Usage for space heating, however, proved to be completely uneconomic. Domestic hot water systems, instead, retained attention. They can be used year-around and have a much larger share in the hot water energy bill than space heating systems have in the heating bill. Of course, in the past, energy use for domestic hot water was only a fraction of the energy needed for space heating. As buildings became much more energy efficient, that fraction slowly increased, to attain a close to 50% share in today's very low energy homes built in countries with a cool climate. That fact could turn solar boilers into an economic efficiency option. To get better knowledge of the avoided energy, two private homes got a fully monitored solar boiler installed. Logging started in January 2005. In the paper, the measured data for one of the homes are commented. The data gained are also compared with the avoided energy consumption, as predicted with the energy performance methodology. An economic evaluation is added.

KEYWORDS

Solar boiler, on site monitoring, energy performance, economy

INTRODUCTION

Active solar was a favorite topic after the first energy crisis of 1973. Most of the work done in those days focused on space heating, as up to 75% of the energy in buildings served that purpose (Anon, 1980). The choice proved to be disappointing in regions with low solar irradiation in winter. In fact, active solar had only sense in dwellings with very low net energy demand. That, however, meant a shorter heating season, leaving only the months with low irradiation as main demand period. The result was a loss by active solar of much of its impact. At the same time the collector area needed was impressive and the storage vessel space demanding, while a boiler was needed to guarantee power. All that kicked active solar out of the market.

Things differ with solar boilers (IEA REWP, 2002)(Anon, 1987). There, the solar trap does not exist. On the contrary, a solar boiler generates usable heat year around. However, domestic hot water represented only a small share in the domestic annual energy usage. Only with the advent of very low energy dwellings that share increased to a level that could turn solar boilers into a defendable measure. Anyhow, today, some in Belgium dream of widespread solar boiler use. Hence, that step should not be set before enough data are available that prove its economical reliability in cool, humid climates. Results of that kind are discussed in the paper. First the dwelling and the solar system are presented. Then the monitored results are compared with the predicted values according to the energy performance methodology. Finally, conclusions are drawn.

DWELLING AND ENERGY USE

The two story dwelling, with a heated volume of 506 m^3 for an exposed envelope surface of 349 m², resulting in a compactness V/A of 1.45 m, was built in 1957 and retrofitted in the eighties (Hens, 1993). The retrofit included an upgrade of the thermal quality (see table 1) and the air-tightness. The dwelling also got a stack driven ventilation system, while the existing central heating was equipped with a high efficiency boiler, a pump driven circulation and a pressurized expansion vessel. Domestic hot water remained separate, using an electrical 200 l boiler.

TABLE 1
Envelope: surfaces and U-values

Envelope part	Surface m²	U-value (W/(m².K)) Before retrofit	After retrofit
Cavity wall	106.6	1.25	1.25
Windows	32.1	4.60	1.84
Pitched roof	91.8	2.35*	0.33
Floor (above cellar/above grade)	78.3	1.32/0.38	0.5/0.38
Partition wall with car port	38.7	1.3-2.3	0.27

*: measurement gave a value of 1.42 W/(m².K) for the SW-pitch and 1.14 W/(m².K) for the NE pitch, proving that quite some air outflow by stack existed

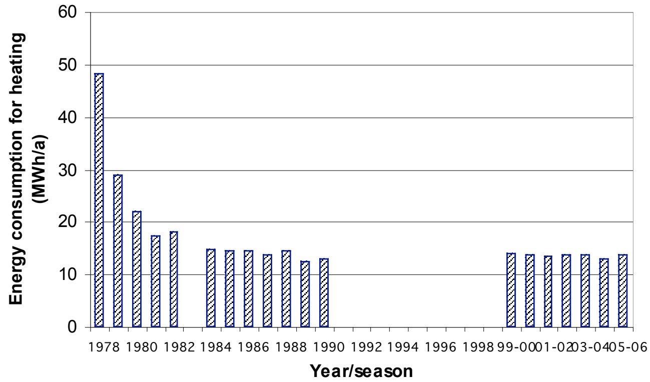

Figure 1 Energy consumption for heating between 1978 and 2006

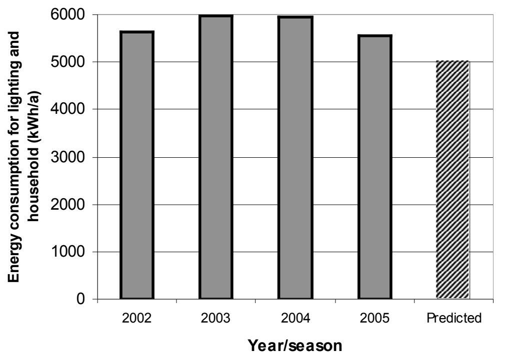

Figure 2 Electricity consumption between 2002 and 2005, comparison with the predicted usage for lighting and household (Hens et al, 2001)

Figure 1 shows the annual energy consumption for space heating as noted between 1978 and 2006. Avoided annual usage by all measures taken, mounts to some 35 GWh, representing a return in energy prices of 2005 of 976 €/a TVA included. Figure 2 informs on the electricity consumed for domestic hot water, lighting and household.

SOLAR BOILER

The solar boiler consists of a 2.75 m² large collector with a slope of 40°, looking South West, coupled to a tank of 120 l, which stands in series with the original domestic hot water boiler of 200 l, see figure 3. The single glazed collector has a selective black surface and is insulated with 5 cm mineral wool at the backside. The pump in the solar loop is of low power, while all piping, in the case being copper with an exterior diameter of 14 mm, is insulated with a 1.5 cm thick PU-shell.

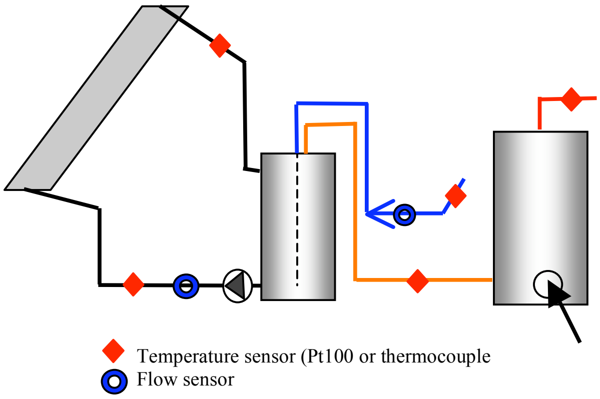

Figure 3 Solar boiler, measuring points

The cold water enters the solar tank, where it is heated by the collector. Each time domestic hot water is tapped, a same amount of preheated water moves from the solar tank to the original boiler. There it is post-heated electrically. Measuring devices include flow sensors on the collector loop and the cold water supply, temperature sensors on the collector supply and return line, the cold water supply, the connection between solar and existing boiler and the hot water supply. Measurements ran on a minute basis, while electricity consumption by the hot water tank and the pump were monitored per five minutes. All data are stored on hard disk for further analysis.

AVOIDED ENERGY AND CO_2-EMISSIONS

According to the energy performance methodology

The Flemish energy performance (EP) methodology honors the use of a solar boiler. Calculation of the net annual energy demand is based on the assumption that each inhabitant uses 30 l of domestic hot water per day, heated from 10 to 60°C. That means a net power demand of 72.7 W per inhabitant, which was rounded to 80 W. Statistically spoken; the number of inhabitants should be proportional to the volume of the dwelling. Until 192 m^3, one inhabitant is considered. Then, each 290 m^3 in plus adds another one. As continuous function, one gets P_{DHW}=max(80, 80+0.275(V-192) in W, giving a net power demand in the case being of 166.4 W. The gross annual energy demand is then found by adding the losses by stagnant hot water in the pipes after tapping. These mainly depend on pipe length between boiler and kitchen and boiler and bathroom, in the case being 8.51 and 10.85 m, resulting in a system efficiency of 0.69. End energy consumption finally is found by first subtracting the solar boiler input from the gross demand and then dividing the result by the production efficiency. Solar boiler input depends on the solar system efficiency:

$$\eta_{as,water,m} = \min\left[\max\left(0, 0.16 + 0.2\frac{Q_{water,gross,m}}{Q_{as,m}}\right), 0.8\right] \qquad \text{Eqn 1}$$

with $Q_{water,gross,m}$ the monthly gross energy demand for domestic hot water production in MJ and $Q_{as,m}$ the total monthly irradiation on the collector in MJ. Application on the case being gave the results of table 2. Apparently, the solar system could cover 46% of the end energy needed.

TABLE 2
Domestic hot water, annual end energy with and without solar boiler according to the EP-methodology

Month	Net demand MJ	Gross demand MJ	End energy,no solar boiler MJ	Usable solar gain MJ	End energy, solar boiler MJ	Avoided energy MJ
J	446	646	922	187	657	
F	402	583	833	205	536	
M	446	646	922	284	521	
A	431	625	893	332	422	
M	446	646	922	384	372	
J	431	625	893	386	347	
J	446	646	922	378	378	
A	446	646	922	375	395	
S	431	625	893	323	430	
O	446	646	922	263	544	
N	431	625	893	196	612	
D	446	646	922	174	674	
Annual	5246	7601	10859	3487	5888	4971

The annual benefit using the electricity prices of 2005 mounted to € 84.4 TVA included. With an investment of € 3411, that results in a pay-back at constant prices of 40 years, i.e., much longer than the service life of 25 years. In prices of 2004 the benefit was € 143, giving a pay-back of 23.8 years. A net present value approach over 25 years with as starting value the benefit of 2004 predicted profit at the end of the period for an annual increase in electricity price close to the depreciation factor. Using the benefit of 2005, instead, demanded an annual increase far beyond that factor! Or, lower electricity prices in a liberalized market dissuade from investing in renewable energy. One positive point: avoided CO_2 does not change, it totals 408 kg/a.

As measured

Hot water consumption

The daily mean domestic gross hot water consumption, derived from the output of the flow meters, totaled 24.4 l/(day.person). The net consumption, which is needed for comparison with the EP-methodology, accounts for tapping losses. That correction represented some 2.7 l per inhabitant per day, resulting in a net consumption of 21.8 l, 33.8% lower than the EP assumes.

Average temperature difference between domestic hot water and cold water supply

The EP takes 50°C as temperature difference between hot and cold water. In the case being, an average of 35.2°C was measured, with peaks passing 50°C, i.e. 29.7% lower. The temperature of the cold water was not 10°C but varied from 12°C in winter to 18°C in summer. The lower temperature difference and lower consumption decreased the net power for domestic hot water to 74.5 W instead of 166.4 W.

Enthalpy flows and energy usage measured

Both are given in Table 3.

TABLE 3
Domestic hot water, measured monthly energy flows

Month	Gross demand MJ	From solar collector to solar boiler MJ	From solar boiler to hot water tank MJ	Electricity supplied MJ	Total without solar support MJ	Avoided energy MJ
J	278	93	84	207	291	
F	167	125	84	147	231	
M	260	208	165	158	324	
A	240	264	211	136	347	
M	201	311	252	97	348	
J	179	312	244	62	307	
J	129	212	154	86	240	
A	218	249	222	107	328	
S	215	252	217	94	312	
O	238	186	192	122	314	
N	251	68	95	190	285	
D	244	53	38	227	265	
Annual	2619	2332	1958	1632	3591	1958
			Pump	243	Pump included	1715

Positive is that the percentage of avoided energy is higher than calculated with the EP-methodology. Negative is that the quantity avoided is only 41% of that predicted, while the avoided CO_2-emissions decrease to some 141 kg/a.

Comparison with the EP-methodology

We first reapplied the EP-methodology, now starting from the measured net power demand of 74.5 W. The results are shown in figure 4.

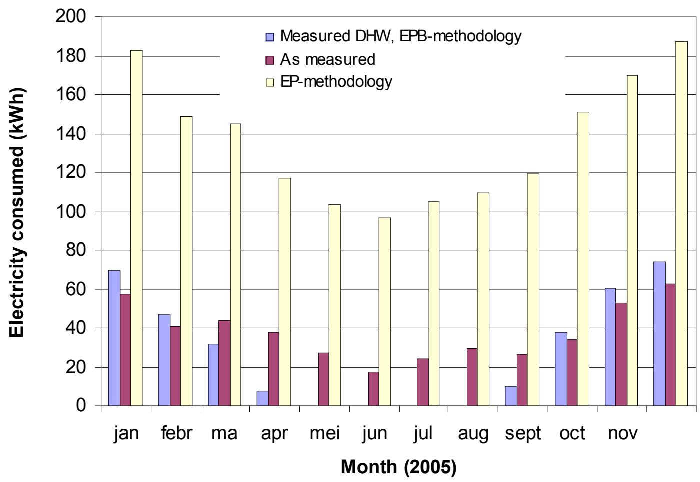

Figure 4 Monthly energy consumption for domestic hot water with a solar boiler in series with the existing boiler as predicted with the EP-methodology, as measured and as predicted by the EP-methodology, using the measured net energy demand.

The figure reveals something strange. The EP-methodology still predicts more avoided energy for domestic hot water than measured, in the case being 1013 kWh/a against 544 kWh/a. A scrutiny in depth learns that the EP-methodology underestimates the system efficiency –69% while 89.6% was measured- but mismatches the production efficiency. In fact, a model calculation revealed that the heat losses of the existing boiler represented some 279 kWh on an annual basis. The monthly loss is somewhat higher in winter than in summer, but the differences are minimal. Adding that number to the gross energy demand measured gives 1007 kWh/a as end energy use, which is close to the measured 997 kWh/a. Hence, the boiler losses should not be represented by constant production efficiency but added as an energy loss to the gross annual energy demand.

Are there ways to confirm the results as measured, i.e., an avoided energy usage equal to 544 kWh minus the pump consumption of 67 kWh/a? The answer comes from analyzing the electricity bills. Between 2004 and 2005 a decrease of 379 kWh was noted, i.e. less than 476 kWh. The years before, anyhow, oscillations up to 349 kWh in plus were seen. As the sum of both is larger than 476 kWh, 476 kWh less for domestic hot water is a plausible result. That gives 4284 MJ/a in terms of avoided primary energy, i.e. only $1/8^{th}$ of the 35 GWh avoided by better insulation, better air-tightness and a more performing heating system.

CONCLUSIONS

With as objective getting field data for evaluation, a single family house was equipped with a solar boiler in series with the existing domestic hot water boiler. A calculation according to the EP-methodology promised up to 4971 MJ/a of avoided end energy consumption, which In terms of primary energy equaled 12 427 MJ/a. The measured results gave numbers far below that promise. Pump included, energy consumption went down with 1715 MJ/a, i.e. 4287 MJ/a in terms of primary energy. Reasons for that difference were threefold. Domestic hot water consumption was lower than assumed in the EP-methodology. On the average, the water was not heated to 60°C but only to 45.2°C and using constant production efficiency proved to be a wrong choice. On the contrary, a more or less constant heat loss term for the existing boiler had to be considered. All three further erode the already hardly existing economic benefits, as lower electricity prices in a liberalized market also do.

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