CALIBRATION OF AN ENERGYPLUS SIMULATION MODEL BY THE STEM-PSTAR METHOD

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ABSTRACT

The PSTAR (Primary and Secondary Terms Analysis and Renormalization) method was developed by the National Renewable Energy Laboratory (NREL) to determine the key thermal parameters of a building from short-term outdoor test results. This paper shows an application of the PSTAR method as a quantitative guidance to calibrate a detailed thermal model of a dwelling. An existing dwelling sited in southern Spain is used as a case study. The entire process comprises: A) Starting from audit data, a detailed EnergyPlus model of the building is created. B) Some experimental tests are carried out: blower door test, thermographic inspection, determination of thermal resistance of some envelope components using heat flux meters and the STEM (Short Term Energy Monitoring) test procedure. C) The PSTAR method is used to obtain quantitative information about the model ability to reproduce three primary thermal parameters of the actual building: the building heat loss coefficient, the charge/discharge of the building mass coupled with variations of the indoor temperature and the solar gains. D) The EnergyPlus model is reasonably calibrated using all information available. As a result, a calibrated model is obtained, whose performance shows good agreement with measured data, yet some caveats still remain in the calibration process. Finally, some modifications to the STEM test are suggested in order to obtain a better experimental data set.

INTRODUCTION

The basic dilemma in building model calibration is that a realistic thermal model of a building tends to be complex and has by far more parameters than can be estimated from performance data. Thus, calibrating a model by varying its input parameters can be rather problematic. The STEM-PSTAR method is an attempt to solve this problem. The method has been used generally on detached houses, see Balcomb et al.(1993) and also has been experimentally validated in Judkoff et al. (2000). PSTAR stands for Primary and Secondary Terms Analysis and Renormalization, and was developed by the National Renewable Energy Laboratory (NREL), see Subbarao (1988). Heat flow into the house air is mathematically separated into terms relating to the effect causing the heat flow. The sum of the terms should be equal to zero at each hour if energy is to be balanced. The terms are listed in table 1 with the sign convention that a heat flow that heats up the indoor air is positive. Each of these macro-terms is computed as convenient, usually by simulation of a detailed building model, which is sometimes called "micro" level simulation. This arrangement of the heat flows is directed to a subsequent calibration of the most relevant terms in the heat balance. These are called "primary" terms, and usually are: the building steady heat loss Q_L, the charge/discharge of the building mass coupled with variations of the indoor temperature $Q_{in,storage}$ and the solar gains Q_{sun}, see table 1. When measured data is used, the heat balance is not fulfilled and three renormalization factors are introduced. These are P_L,$P_{in,storage}$ and P_{sun}, and are simply scale factors for the primary heat flows. They are used to minimize the Root Square Mean Error (RSME) of the heat balance. Measured data is obtained via the STEM procedure. STEM stands for Short Term Energy Monitoring, and is described in some detail in Subbarao (1988) and Balcomb et al. (1993), and more recently in Judkoff et al. (2000). It is an experimental protocol with the aim to enhance the primary heat flows over the remaining ones in order to allow a robust identification of the renormalization factors. It consists of three periods, an initial period of co-heating, during which inside air temperatures are maintained at a uniform and constant value, using several portable electrical heaters. The objective is to enhance the steady state heat loss to the environment Q_L over the other heat flows. Then, there is a cool-down period when the heaters are shut-off and the inside air temperature changes. The objective is to enhance the internal mass charge/discharge heat flow $Q_{in,storage}$. Finally there is a period when the indoor air temperature is allowed to freely float, and can be used, altogether with the previous periods, to calibrate the solar gains term Q_{sun}. The result should be a calibrated macro-level building model, i.e. a model that minimizes the heat balance RMSE when using measured data. The problem at this point is that the PSTAR building model is not a physical model any more, but a grey-box model, so it lacks versatility. Alternatively, this paper proposes to preserve a physical micro level model of the building and to use the PSTAR method to evaluate whether the model captures the primary thermal characteristics of the actual building. The renormalization factors will provide quantitative information about how far is the model from the actual building. Certainly, the calibration of a micro level model implies varying its input parameters, which is problematic and even arbitrary because it depends on the judgement of the user, who will need to make some assumptions. Some extra information from additional experimental tests may contribute to support the abovementioned assumptions. In this case the tests were a blower door test, a thermographic inspection and the determination of the thermal resistance of some envelope components using heat flux meters. Next section describes how the EnergyPlus simulation program can be used to obtain the PSTAR macro terms, then a case study that illustrates the whole procedure is presented.

ENERGYPLUS TO OBTAIN THE PSTAR MACRO TERMS

EnergyPlus is a general purpose building simulator, and a useful tool for computing the PSTAR heat flow macro terms. Each term requires an specific simulation scenario, in order to isolate the effect studied. The last column of table 1 summarizes the settings required. Most of these simulation scenarios use special environmental conditions that can be obtained using modified weather files. Measured temperatures and heat flows from adjacent spaces can be included as inputs to the simulation using schedules linked to external files. An underlying assumption in the PSTAR method is the linearity of the model, so that the superposition principle could be applied and the heat balance fulfilled. Long wave radiation exchange and non constant convection coefficients make a standard EnergyPlus simulation model non linear. A first approach may be to force the model to be linear by assuming some fixed values for the convective film coefficients and eliminating the long wave radiation exchange by setting a very reduced value of thermal emissivity for the materials. In this paper, the PSTAR is used just as a tool to help in the calibration of the detailed micro level model, so it is not so crucial to keep linearity as far as the renormalization factors keep on providing useful information. Thus, the standard EnergyPlus models accounting for long wave radiation and non constant convection film coefficients are keeped. Another problem is that there are some surfaces where the heat flux is measured, e.g. the wall next to the health center. The measured flux is composed of various terms: steady-state conduction, charge and discharge effects due to changes in inside and outside temperatures, and also some heat flow that can be related to solar radiation, passing through windows and being distributed on the interior surfaces. It must be avoided to account twice for this last effect, once into the measured heat flux, and twice into the term Q_{sun}. Simply eliminating these surfaces from the simulation model will not work, because the entering solar radiation will be distributed on the remaining interior surfaces. A way to solve this problem is to use a fictitious surface, with the same solar absorptance than the actual one, but highly conductive and with a very reduced (ideally zero) convection coefficient. On the outer side of the fictitious surfaces, the same temperature of the zone is imposed. Therefore, solar radiation on those surfaces will be absorbed, but will never be rejected into the room air.

CASE STUDY

It is a house sited in the village of Montecorto, Spain. lat.: 36º49’ N, long.: 5º18’E, elevation 500 m.

Figure 1 South oriented façade.

There are ten houses in a row, the studied one is sited at the east boundary of the row, quoted as number 1 in the figure 2. There are two main orientations exposed to the exterior environment, the south façade, (see figures 1 and 2) which is turned 14º to east, and the north façade. Part of the east façade is exposed to the exterior environment,and the other part is an internal partition to an adjacent building, which is a health center that can also cast some shadows on the south façade of the house nº1 during the first hours of the day, see figure 4. The west wall separates houses number 1 and 2. The roof is flat and there is a slightly ventilated crawl space beneath the lower storey of the house. There are two storeys: downstairs there is a living room, a kitchen and a small laundry room. Upstairs there are three bedrooms, and a bathroom, see figure 3.

Table 1
PSTAR method macro terms and calculation method of each term using EneryPlus simulations.

TERM	DESCRIPTION	METHOD
Q_L	Steady state gain to house air from outside air, calculated by multiplying the building loss coefficiente (BLC) times the outside-inside temperature difference.	Simulation with fixed inside and outside temperatures, e.g. 20-0º C. No solar radiation, sky temperature matches the outside dry temperature. Other boundary conditions apart from the exterior environment are set equal to the inside air temperature. Of course, the BLC calculation can be done in a "traditional" manner but, with this simulation, one can be sure of the inbuilt BLC of the simulation model.
$Q_{in,storage}$	Heat flow positive if the thermal mass of the building is releasing heat into the house air, which occurs when inside air is cooling down.	Simulation with fixed outside temperature, e.g 20ºC, no solar radiation, sky temperature is equal to the outside air temperature. Other boundary conditions apart from the exterior environment are set equal to the outside temp. An ideal HVAC system forces the inside temperature to match the measured temperature from the actual building during the STEM monitoring period. The sensible heating/cooling rate of this ideal HVAC system is the summation of $Q_L + Q_{in,storage}$. The latter can be obtained by subtraction.
Q_{sun}	Heat flow to the house air due to solar gains. This includes solar gains through the windows, heat stored into building internal mass and heat flow through the external walls due to solar radiation absorbed on the exterior surfaces.	Simulation with fixed outside temperature, e.g. 20ºC, solar radiation as measured, sky temperature is set equal to the outside air temperature. Other boundary conditions apart from the exterior environment are set equal to the outside temp. An ideal HVAC system forces the inside temperature to match the outside temperature. The cooling load is Q_{sun}.
Q_{aux}	Measured heat flow from the electric heaters.	It is measured in field during the STEM monitoring period.
$Q_{\inf il}$	Heat flow due to infiltration air.	Can be estimated using the Sherman-Grismrud model, based on the measured leakage area, the inside-outside temperature difference and the wind speed.
$Q_{out,storage}$	Heat flow to the house air due to changes in outside temperature. Positive when outside temperature is cooling down.	Simulation with outside temperature as measured, no solar radiation, sky temperature is set equal to the outside air temperature. Other boundary conditions apart from the exterior environment are set equal to the inside temp. An ideal HVAC system forces the inside temperature to be constant e.g. 20 ºC. The sensible heating/cooling rate of this ideal HVAC system in each hour is the summation of $Q_L + Q_{out,storage}$. The latter can be obtained by substration.
Q_{sky}	Heat flow to the room due to the depression in sky temperature below outside air temperature. Normally negative	Simulation with outside temperature fixed, e.g. 20ºC, no solar radiation, sky temperature matches the depression value below outside air temperature.An ideal HVAC system forces the inside temperature to match the outside air temperature. The sensible heating rate of this ideal HVAC system in each hour is -Q_{sky}. The sky temperature is estimated based on the measured outside temperature, clearness index and relative humidity, using expressions from Martin and Berdahl (1984) and Kasten and Czeplak (1979).
$Q_{adj,temp}$	Heat flow due to conduction from an adjacent space, where the temperature can be measured. In this case, the crawlspace.	Simulation with outside temperature fixed, e.g. 20ºC, no solar radiation, sky temperature equal to the outside temperature. Temperature of the adjacent space as measured. Inside temperature constant and equal to the outside air temperature. The sensible heating/cooling of the HVAC system is Q_{crawl}. This term is composed of two parts, a steady-state conduction part, and a transitory part due to changes in the adjacent space temperature. These parts can be calculated if necessary in the same way as $Q_{out,storage}$
$Q_{adj,flux}$	Heat flow due to conduction from an adjacent space, not accesible, so the temperature cannot be measured. A heat flux meter is used to measure the actual heat flux on the inside surface.	Measured via one or more heat flux meters.

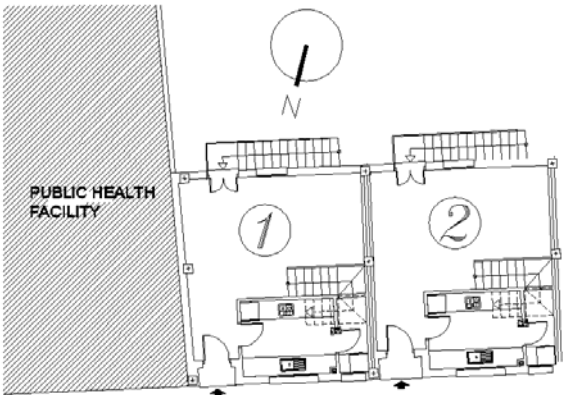

Figure 2 Plan of the studied house (number 1) orientation, and boundaries.

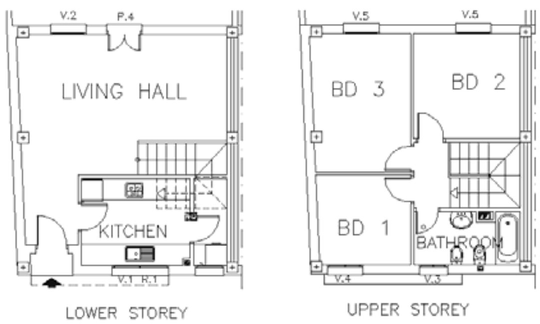

Figure 3 Interior distribution of the house.

Table 2
Summary of opaque constructions. Data extracted from building plans.

Element	Description	Solar Absorp.	U (no film) W/m2-K	weight Kg/m2
External Walls	Cavity wall, PUR 30 mm	0.3	0.68	298
Flat Roof	Concrete, XPS 30 mm	0.6	0.80	423
Floor	Concrete No isolated	0.3	3.50	326
Internal Floor	Concrete	0.3	-	346
Internal partitions	Brick wall	0.3	3.33	133
Partitions to adjacent buildings	Brick wall,no isolation	0.3	3.33	133

The house was built in year 2006, and the experimental tests were performed during December 2007. The house had never been occupied, thus it had no furniture at all. Table 2 shows a summary of opaque constructions. Windows have clear simple 6 mm glazing with a 12 mm width, al-no break frame. The outside reveal depth is about 25 cm. The test was performed with the windows blinds fully raised (opened). There is a wooden exterior door in the north façade. Table 3 shows data about walls with windows and/or doors and table 4 summarizes the wall areas.

Table 3
Data about walls with windows.Area in m^2.

Façade	Windows number /area(2)	Doors number/area
North	4 / 2.9	1/ 2
South	4 / 4.6	-
Total	8/ 7.5	1/2

(1) Area of just glazing without frame.

Table 4
Summary of wall area classified by its boundary condition. Area in m^2.

Boundary	Wall	Area Gross / net(1)
Exterior env.	North	23.6/ 16.8
Exterior env.	South	24.6 /17.3
Exterior env.	East	13.3
Exterior env.	Roof	37.5
Crawl space	Floor	37.5
Health center	East partition	13.3
House num. two	West partition	27
Zone internal	Internal floor	37.5 x 2(2)
Zone internal	Int. partitions	50 x 2(2)

(1) Net area is the gross area minusthe area of windows, frames and doors.
(2)Total wall area exposed to internal air, that is why it has to be doubled

An EnergyPlus building model with one thermal zone is built from the audit data (audit model), special attention is paid to the geometry and surrounding buildings that may cast shadows, see Figure 4.

The experimental setup.

A Hobo weather station was used to record environmental data, such as dry temperature, relative humidity, global horizontal solar radiation, global vertical south solar radiation and wind speed. Indoor, a Campbell CR1000 datalogger recorded six room temperatures, measured with T-termocouples. The CR1000 was programmed to control the indoor temperature individually switching on and off six portable electrical heaters, following the STEM protocol. The electrical power was measured with Hobo CTV hall effect transducers. A separate datalogger Hobo U-23 was used to record temperature in the crawl space beneath the house. It was impossible to access the health center, neither the house number two, so Hukseflux HFP01 heat flux meters were located on the inside face of the partition walls. A GSM modem was used to transmit the data recorded by the CR1000 for remote control and analysis.

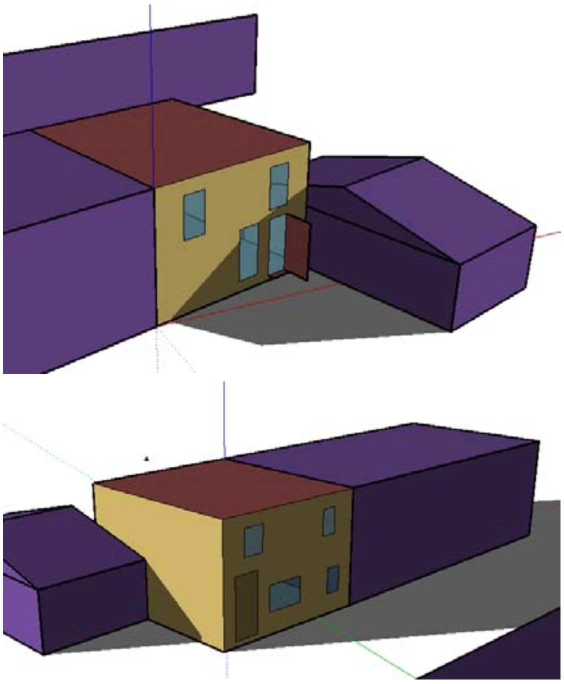

Figure 4 EnergyPlus model of the house, visualized with GoogleSketchUp. Upper image: view from south. Lower image: view from north.

Blower door test.

A Minneaoplis Blower Door model 4 was used to pressurize/depressurize the house following EN 13829 standard. Intentional openings located in the kitchen were closed. The LBL ELA @4Pa obtained was 367 cm^2. This value was used to estimate the infiltration rate via the Sherman-Grismrud model.

Thermographic inspection.

A FLIR ThermaCAM P640 was used to inspect the building envelope following EN 13187 standard. The test was performed on Dec 5th, four days after the beginning of the co-heating period to avoid start-up effects, and just before dawn to avoid solar radiation effects. The difference between the inside temperature and the outside environment was about 15 ºC. Infrared images showed important thermal bridges, see figure 5, both structural elements and around the windows and doors. The other façades of the building showed similar thermal bridges. These thermal bridges were neglected in the first simulation model built, but after the PSTAR analysis were calculated using EuroKobra and introduced in the model.

In-situ U determination with heat flux meters

During the co-heating period, Hukseflux HFP01 heat flux meters were used to determine the thermal transmittance of the north and south façades, following ISO 9869 standard. TandD RTR-52 dataloggers were used to measure the surface temperature on both sides of the wall. Results show a thermal transmittance (w/o film coefficients) of 0.73 W/m^2-K for the south façade and 0.78 W/m^2-K for the north one, slightly over the audit value, but not too far. Keeping in mind the uncertainty of this kind of test, it was decided that a modification of the values of table 2 was not justified enough.

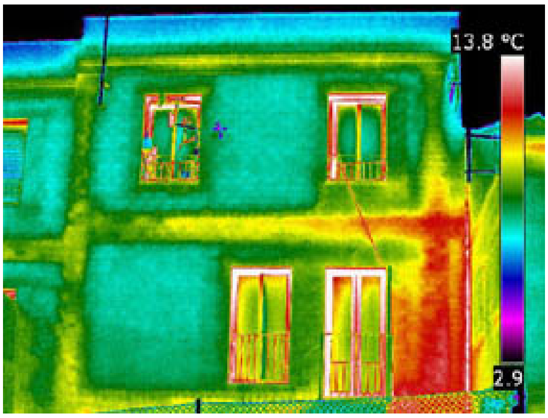

Figure 5 Infrared image of the south façade.

RESULTS OF THE PSTAR ANALYSIS

The coheating period of the STEM test was started on Dec 1st, 2007. Heaters were shut off at Dec 14th 00:00 to start the cool-down period, the test continued allowing the indoor temperature to float until Dec 18th. The figure 6 shows how the electric power necessary to maintain 20 ºC indoor was decreasing during the first four days since the beginning of the coheating period. Since solar radiation and external temperature were similar in those days, it can be concluded that the reason is that the thermal mass of the house was heating up. This is a significant difference with the standard STEM protocol, that uses only one day of coheating, which might be appropiate for lighter constructions. Analyzing the figure 7, the audit model over predicts the indoor temperature, but it is difficult to infer a reason, since there are various heat flows of similar importante in the heat balance. The PSTAR method allows a closer analysis, see figure 8, on December 11th and 12th , during the three last hours of night before dawn, Q_L became significant larger than the other primary heat flows (Q_{sun} and $Q_{in,storage}$). The RMSE in the heat balance was 880 W always positive in those hours. The dominant heat flow should be the main responsible for the error in the heat balance, so those hours are selected as a convenient time window to adjust the heat losses renormalization factor p_L so that the RMSE is minimized in that time window. On the other hand, during the cool-down period, figure 9, during the hours before dawn, the $Q_{in,storage}$ heat flow becomes rather important, so the abovementioned hours are selected as a convenient time window to adjust $P_{in\_storage}$, minimizing the RMSE in that time window. Finally, the whole test period is selected for the renormalization of Q_{sun}, minimizing RMSE in the whole test period. The iterative process converged to the following renormalization factors: P_L=1.54, $P_{in\_storage}$=1.57 P_{sun}=1.02, meaning than the BLC and thermal mass of the actual building have been underestimated in the audit model. However, solar gains appear to be properly estimated.

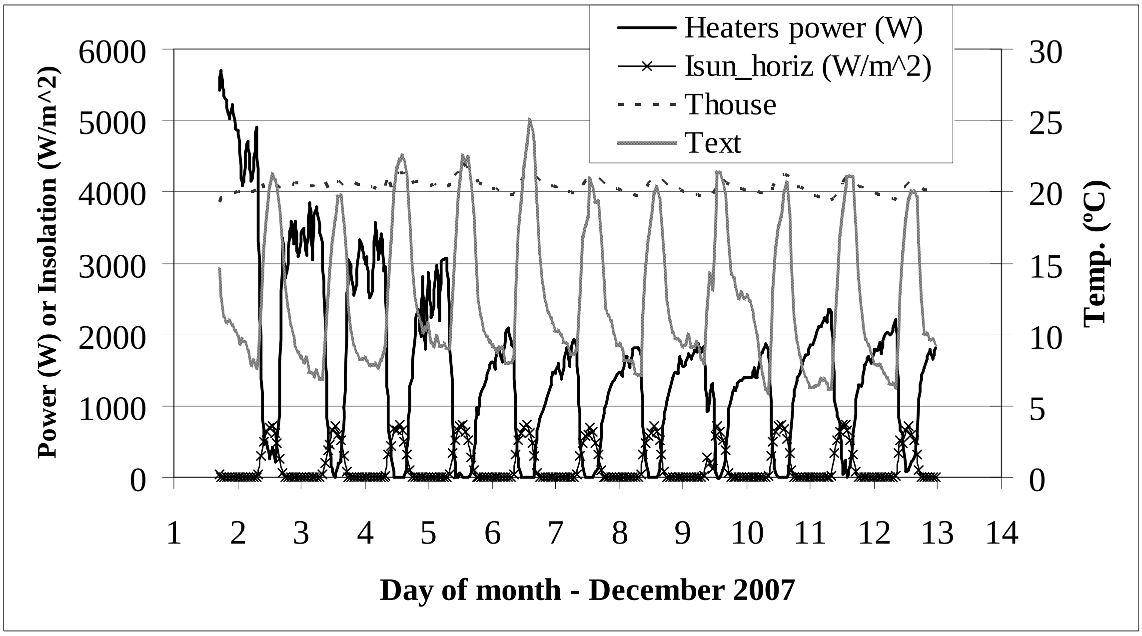

Figure 6 Some magnitudes measured during the coheating period.

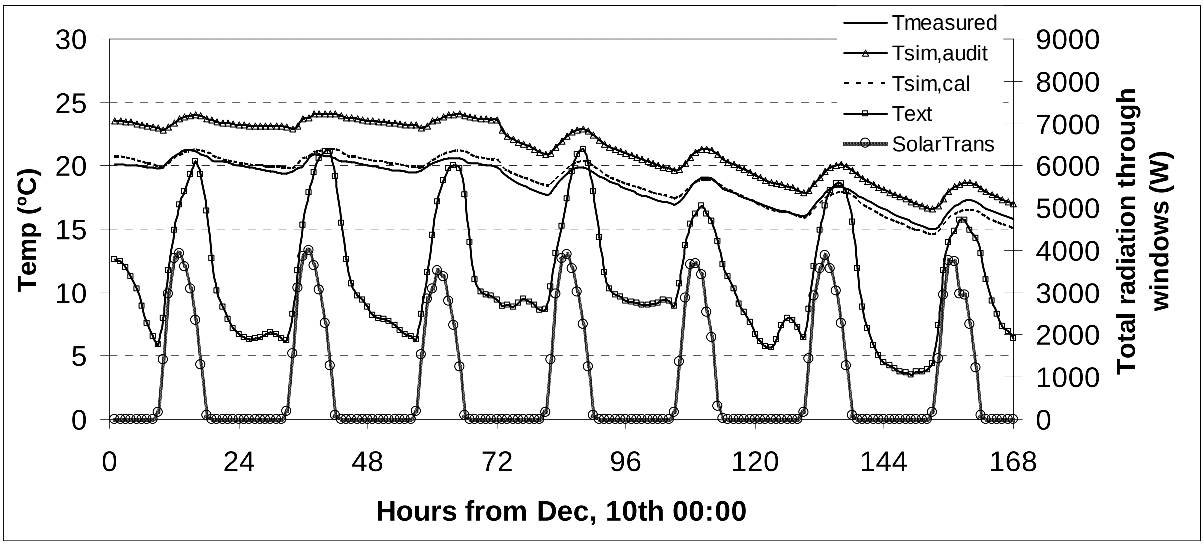

Figure 7 Comparison of simulated and measured temperatures..

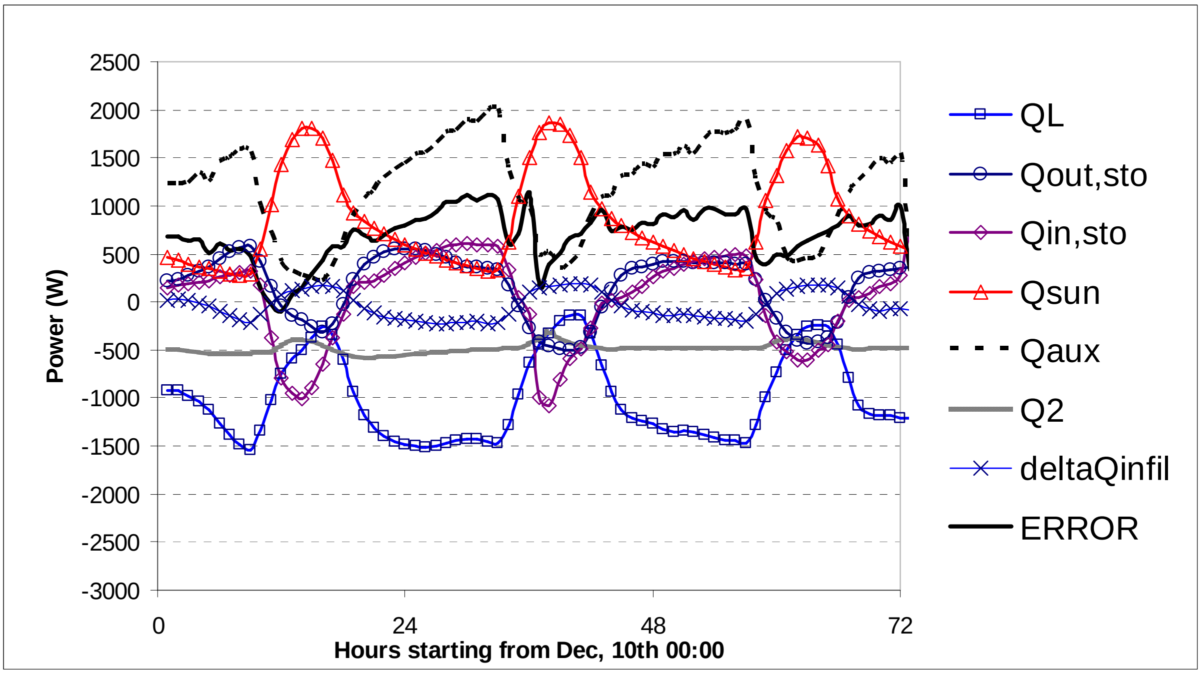

Figure 8 Audit model. Heat flows for the co-heating period. In this figure, Q_L includes a base infiltration component, deltaQinfil is the variation of infiltration around the base component.Q2 is the sum of all the secondary heat flowss not explicitly shown for clarity purposes.

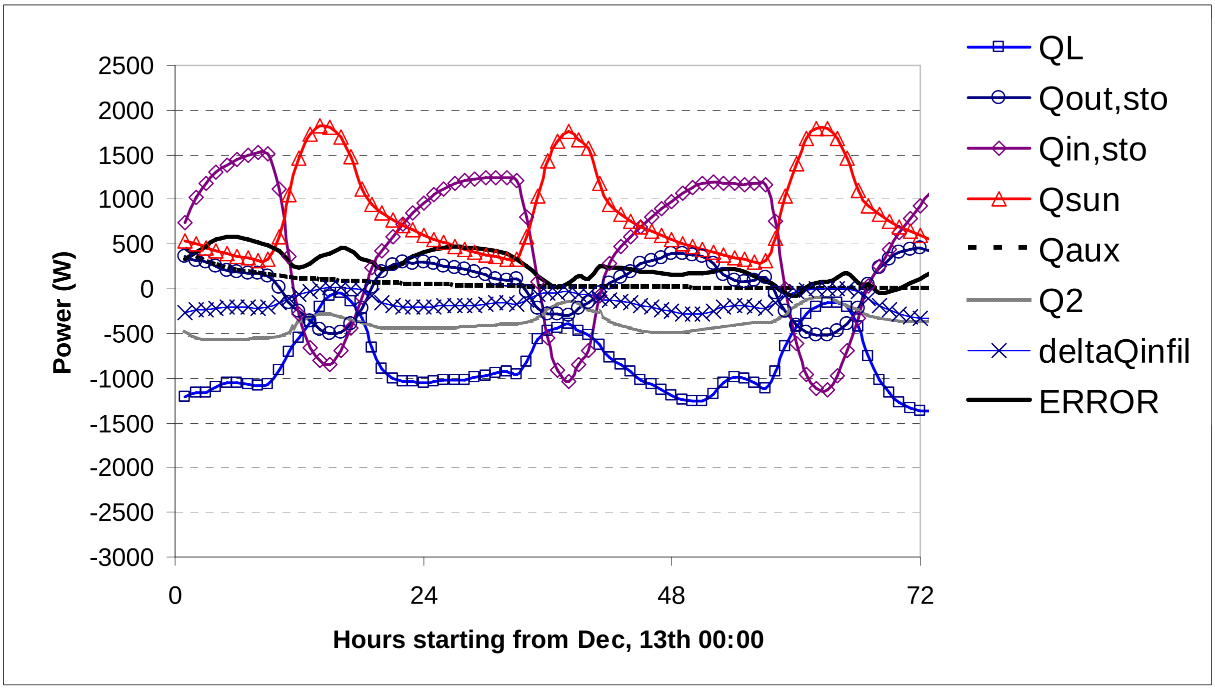

Figure 9 Audit model. Heat flows for the cool down period. In this figure, Q_L includes a base infiltration component, deltaQinfil is the variation of infiltration around the base component.Q2 is the sum of all the secondary heat flowss not explicitly shown for clarity purposes.

CALIBRATION OF THE MODEL

The BLC of the initial audit model is 106 W/K , plus 20 W/K related to the mean value of the estimated infiltration rate (0.4 ACH) during the monitored period. Additional heat loss coefficient of 68.7 W/K to the crawl space is excluded as this heat flow was considered as a separated, secondary term. Therefore the total combined BLC is 126 W/K. Thus, the factor P_L=1.54 means 68.25 W/K of additional BLC. Using Eurokobra, the additional BLC related to the thermal bridges was estimated in 60.5 W/K, which is a comparable value to the abovementioned 68.25 W/K. Therefore, the impact of thermal bridges is a plausible explanation to the discrepancies between the audit model BLC and the one inferred by the STEM-PSTAR method. The simulation model was modified, introducing several sub-surfaces to account for the actual thermal bridges. Additional thermal mass was added using a trial and error scheme until renormalization factors were close to unity. Finally the simulated temperature is quite close to the measured temperature, see figure 7. Despite the good results, we have found this process quite hazardous, in the sense of user dependent, since one could find some plausible combinations of assumptions, that can lead to reasonable results. Therefore, the modification of any input parameter should be as supported as possible by measurements or documentation. In addition to this, it has been found that, for this case study, the typical experimental data collected by a STEM test cannot sufficiently minimize the interactions between solar gains, mass and heat losses. It is possible that a modification of the test protocol could yield better results, for example, the use of two co-heating periods, one at the beginning and one at the end, will provide both a cool-down and a warm-up periods, which can be useful for a better determination of the thermal mass. In addition to this, closing the window blinds should contribute to a more robust identification of both heat losses and thermal mass. A subsequent period with the blinds fully opened may be used to determine solar gains through windows. Of course, all these modifications increase the time span and cost of the monitoring period.

CONCLUSIONS

Despite the fact of the PSTAR method is somewhat an old technique, it is still useful because it provides quantitative guidance about discrepancies between the simulation model and the actual building. The special arrangement of heat flows provides insights into the thermal performance of the building and helps to identify appropriate time windows to calibrate some important parameters of the thermal model, minimizing interactions between the main heat flows. A case study is presented, and good results are obtained. However, it is found that the process of calibrating a detailed model remains rather user dependent, so every modification of any input parameter should be as supported as possible by experimental or documental evidence. Finally, in order to obtain a better experimental data set, some modifications to the original STEM test are suggested, but these still have to be researched through both simulation and experimental work.

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