Chapter 34
High Quality of Calibration Accuracy for Smart Building Energy-Efficiency Opportunities

G. Mustafaraj

Abstract A well-calibrated model is crucial to accurately represent a building's energy profile. This chapter deals with a building where an underfloor heating system supplied by a geothermal water-to-water heat pump and natural ventilation are the main systems used to maintain comfort conditions. Existing methodologies to establish calibration accuracy are mainly based on whole-building energy consumption comparisons. This research considers whole-building energy consumption with a breakdown of end-use energy consumption. The objective of this work is to develop a two-level calibration methodology which starts with calibration and then continues with the necessary actions for improving building energy efficiency. Finally, the model was simulated to estimate the potential of energy-efficiency improvements. The results of the analysis show that electricity consumption savings and heat released from the heat pump can vary between 20 and 27 % on a monthly basis.

Keywords Calibration • Smart buildings • Energy efficiency • Natural ventilation • Underfloor heating • Water-to-water heat pump • Natural ventilation

1 Introduction

Environmental concerns and the recent increase in energy costs open the door to innovative techniques to reduce energy consumptions. Buildings account for about 40 % of energy consumption in the European Union (EU) [1]. Improvement of their energy performance is a major challenge of the twenty-first century. To this end the new Energy Efficiency Directive was formally adopted by the Council of Ministers

G. Mustafaraj (✉)
International Energy Research Centre IERC, Tyndall Institute, University College of Cork, Cork, Ireland
e-mail: gmustafaraj73@gmail.com

A. Sayigh (ed.), *Mediterranean Green Buildings & Renewable Energy*,
DOI 10.1007/978-3-319-30746-6_34

and European Parliament in October 2012. The main objective of the Directive is to promote the improvement of the energy performance of buildings within the EU through cost-effective measures [2]. Hence, this chapter presents a new calibration methodology with the purpose of increasing the accuracy of building energy models as a necessary action before implementing any energy-efficiency measures.

Past research [3–6] dealt mainly with the calibration process without considering any further opportunities for energy savings. Additionally, research on building energy model calibration has been based solely on simple heating, ventilation, and air conditioning (HVAC) systems [e.g. forced ventilation supplied by air-handling units (AHUs)].

The calibration methodology proposed by Raftery et al. [3] recognises the need for systematic evidence-based decision-making to improve reproducibility and reliability in model calibration. Bertagnolio et al. [4] proposed an evidence-based calibration of a simplified dynamic hourly model which uses technical specifications, measurements, sensitivity and uncertainty analysis to predict whole-building energy use. In 2008, the Royal Institute of British Architects (RIBA) and the Chartered Institution of Building Services Engineers (CIBSE) launched CarbonBuzz, a free online platform allowing practices to share and publish building energy consumption data anonymously [7]. It enables designers to compare predicted and actual energy use for their projects, whilst also allowing for comparison against benchmarks and data supplied by other participating practices. In particular, Hamilton et al. [8] compared the predicted and actual electricity consumption in three building sectors: schools, general offices and university buildings. They demonstrated that the measured electricity demands are approximately 60–70 % higher than predicted in both schools and general offices and over 85 % higher than predicted on university campuses. Despite these works, there is a need for further research to develop new calibration methodologies capable of further reducing the gap between predicted and actual energy consumption.

Thus, the contributions presented in this chapter are as follows. First, a novel methodology is presented based on whole-building energy consumption in combination with an end-use energy consumption breakdown.

Second, our calibration methodology considers in a holistic way the complex interactions of the components of HVAC systems that affect the accuracy of the model (e.g. ventilation types and underfloor heating systems). Third, the algorithm developed represents a complete analysis which includes a calibration process and then the required measures to increase energy savings.

This chapter is organised as follows. Section 2 presents the two levels of the calibration methodology and discusses the algorithm. Section 3 gives an overview of the demonstration building and HVAC plants. Section 4 describes the building simulation activity to identify further opportunities of energy savings. Finally, Sect. 5 provides a conclusion with directions for future research works.

2 Overview of Calibration Methodology

In our calibration methodology, input parameters are specified by an analyst and used by energy simulation programs to reproduce a building's thermal processes, while outputs are energy performances simulated by energy simulation programs, given certain input parameters. Two levels of calibration are performed and use a combination of building, system and measurement data.

Building energy models were developed using EnergyPlus version 8.2 [9]. Throughout the calibration process, hourly and monthly EnergyPlus [9] model outputs related to heat pump electricity consumption, heat pump heat released, building total electricity consumption, natural gas and indoor zone temperatures were compared to measured data. The adequacy of this calibration was evaluated against the ASHRAE Guideline 14 [10], which outlines a way to compare model output with sensor data using mean bias error (MBE) and cumulative variation of root-mean-squared error [CV(RMSE)]. ASHRAE Guideline 14 [10] prescribes the acceptable limits for calibration to hourly data as $10\,\% \leq MBE_{hourly} \leq 10\,\%$ and $CV(RMSE)_{hourly} \leq 30\,\%$, and monthly data as $5\,\% \leq MBE_{monthly} \leq 5\,\%$ and $CV(RMSE)_{monthly} \leq 15\,\%$. Figure 34.1 shows the procedure for model calibration and identification of energy-savings opportunities and is described as follows.

First level of calibration: The first level corresponds to an 'as-built' model of the installation. This version of the model is based on available as-built data (plans, schemes and nameplate data of main HVAC components) and will be used for screening parameters. The data collected at this stage correspond to the information which can be expected when proceeding to an energy audit/inspection of an installation.

Second level of calibration: The second level involves an intensive use of building energy management system (BEMS) records and the monitoring data collected on site by means of the measurement equipment.

The calibration process during level 2 is a more advanced step which consists of an iterative process to identify the most important parameters. The value of each identified parameter has to be estimated/refined. Various direct or indirect measurement techniques can be used for that purpose (e.g. direct indoor or supply temperature measurement or indirect estimation of operating profiles by means of short-term monitoring of some lighting or appliances consumption measurements).

Finally, the second level of the calibration process also includes parameter estimation. These parameters could be building use related (e.g. occupancy, lighting, appliance) or system operations related (e.g. HVAC thermostat schedules). Earlier research demonstrated that occupancy is one of the important factors in the discrepancies between simulated and measured energy performances [11] because the main end users of energy, such as HVAC systems, lighting and appliances, are influenced by occupancy [12]. Throughout the calibration process, model validation was conducted (on hourly and monthly bases) by comparing model output with real measurements.

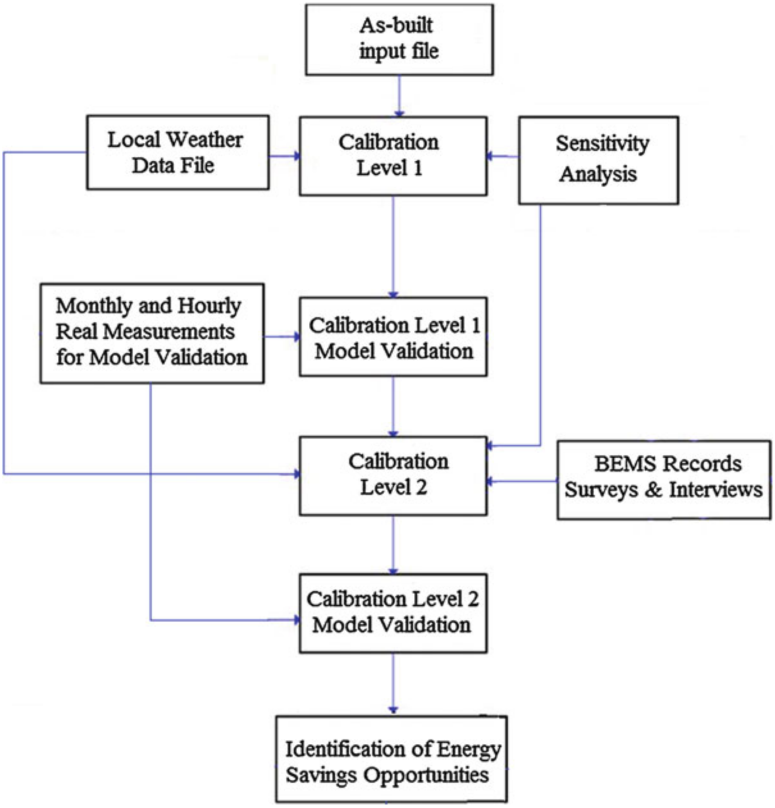


Fig. 34.1 Algorithm for model calibration and energy-saving opportunities

A sensitivity analysis was performed throughout the first and second levels as a screening method to rank non-visible parameters based on how the simulated energy consumption would change in response to changes made to each non-visible parameter.

The Morris method [13] was used in our research to identify the influential parameters because it has been proven valid for screening building energy simulation parameters [14]. This method was found to be suitable for application to building energy simulation models by De Wit [14] since it is not dependent on the properties of the model and requires no assumption regarding linearity or correlations between the inputs and outputs of the model. Heiselberg and Brohus [15] also highlighted other advantages of the Morris method. First, the method can handle a large number of parameters and requires a relatively limited amount of simulation runs. Second, the parameters are varied globally within the range and the whole parametric space can be explored without predefining the probability density function of each parameter. Third, the results are easily interpreted and visualized graphically, as prescribed by Morris [13].

To further increase the accuracy of calibration, a local weather data file is used which was built and based on the data collected from an on-site weather station. Finally, identification of energy-saving opportunities is made to further reduce electricity consumed by the water-to-water heat pump.

3 Overview of Building and HVAC Plants

The Environmental Research Institute (ERI) building in Cork is a three-storey 4500 m^2 research building containing offices, computer laboratories, wet laboratories, a clean room and controlled-temperature rooms. Figure 34.2 shows a 3-D view generated with DesignBuilder [16] using design documents. The geometry of the building model was derived from mechanical ventilation drawings, and DXF files were created from the AutoCAD drawings (DWG).

The building is a reinforced concrete structure providing high levels of thermal mass to allow for natural and mechanical ventilation with night cooling as required. The build-up of the floors, roof, external façades, internal partitions and windows were constructed from as-built structural drawings.

The build-up thermal properties were taken from CIBSE [17] and ASHRAE [18] and are listed as follows:

Fig. 34.2 ERI building 3-D view of design model

- **East and west face**: 250 mm reinforced concrete, 100 mm polystyrene, 25 mm gypsum plaster ($U = 0.258$ W/m^{2}K);
- **South face**: 10 mm hardwood, 40 mm rockwool, 15 mm plywood ($U = 0.848$ W/m^{2}K);
- **North face**: 25 mm rockwool, 38 mm air gap, 250 mm cast concrete, 15 mm hardwood ($U = 0.839$ W/m^{2}K);
- **General flat roof**: 10 mm stone chippings, 20 mm felt/bitumen layer, 75 mm screed, 275 mm polystyrene, 250 mm concrete slab ($U = 0.104$ W/m^{2}K);
- **Internal partition**: 25 mm gypsum plaster, 50 mm cavity, 50 mm glass fibre quilt, 15 mm plywood, 10 mm gypsum plaster ($U = 0.498$ W/m^{2}K);
- **Ground floor and first floor slabs**: 250 mm concrete slab, 275 mm polystyrene void former, 75 mm screed ($U = 0.1$ W/m^{2}K);
- **Lower ground floor slabs**: 750 mm clay, 150 mm stone, 175 mm concrete slab, 50 mm insulation, 75 mm screed ($U = 0.452$ W/m^{2}K);
- **Glazing north**, **south**, **east and west façades**: 4 mm Optifloat/16 mm/4 mm K Glass ($U = 1.7$ W/m^{2}K).

Apart from smaller areas of the building that occupy the central core of the building space (such as toilet, cold rooms, clean rooms and stores) which are mechanically ventilated by five AHUs, the majority of the building is naturally ventilated.

Figure 34.3 is a schematics overview of the HVAC system. The building is heated by an underfloor heating system that is primarily supplied by a geothermal heat pump which taps into a water supply fed from a culvert running adjacent to a nearby river. The underfloor heating operates at a maximum temperature of 38 °C.

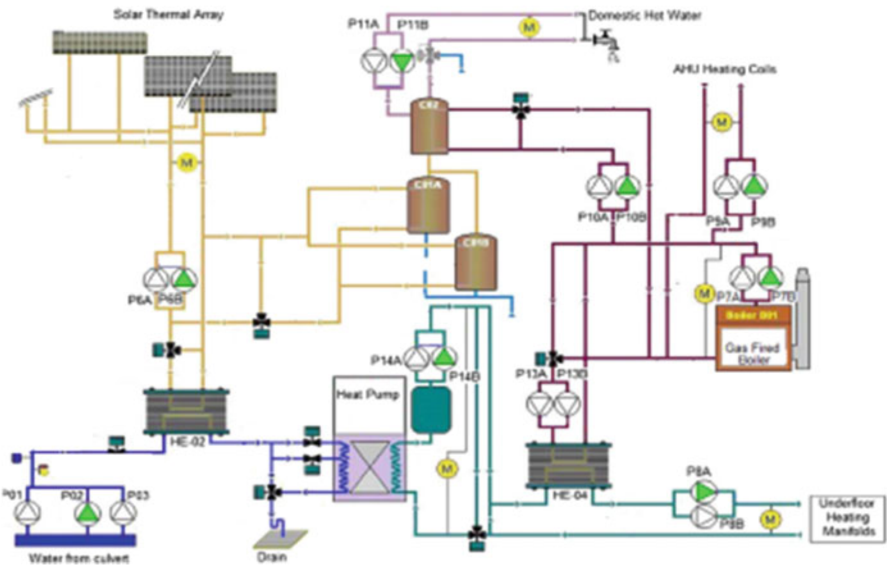


Fig. 34.3 Schematic of HVAC system [11]

Overall, the heat pump (Coefficient of Performance) = 2.4–4.2) meets 80 % of the building's heating requirements, with the balance provided by a condensing gas boiler sized to act as a complete back-up system. The solar thermal collector composed of 28 flat collectors is installed to provide hot water, with the remaining domestic water load provided by a direct gas-fired water heater (Fig. 34.3). It was verified that this heat is only 3–5 % of the heat required by the building.

Consequently, solar panels were included in the EnergyPlus model; however, during the calibration process, no particular attention was given to them.

4 Analysis of Results

The build-up of the floors, roof, external façades, internal partitions and windows of each floor were constructed from as-built structural drawings.

The as-built information was complete and allowed identification of relatively accurate values of envelope component characteristics (e.g. U-values). The selection of the most influential parameters was based on the results of the sensitivity analyses performed in EnergyPlus. Finally, analysis of the results related to model calibration and energy-saving opportunities are presented in Sects. 4.1 and 4.2.

4.1 Calibration

The accuracy of the calibration was evaluated by computing the classical calibration criteria in terms of MBE and CV(RMSE) on an hourly and monthly basis in 2011. During the first level of calibration, fixed values of temperatures were taken from ASHRAE [19] and used as a schedule in Energy Plus. Throughout the first level of the calibration process, the values of MBE and CV(RMSE) on an hourly basis were less than 18.7 % and 36.2 % respectively, while on a monthly basis the value of MBE was less than 8.6 % and for CV(RMSE) it was less than 20.7 %.

In contrast to the first level, during the second level of calibration, the real values of zone temperatures were collected from BEMS at an hourly sampling rate and used in EnergyPlus as the schedule for the temperature.

A comparison between measurements and model output related to the first and second levels of calibration is presented in Figs. 34.4, 34.5, 34.6 and 34.7. An analysis of the results demonstrated improvements in the model prediction as we moved from the first to second level of the calibration process.

In addition, the present research also considered comparisons between simulated and measured data based on hourly data (Figs. 34.8, 34.9 and 34.10).

Finally, after applying the second level of calibration, the values of MBE and CV (RMSE) on an hourly basis were less than 11.4 and 33.5 % respectively, while on a monthly basis the value of MBE was less than 6.1 % and for CV(RMSE) it was less than 16.5 %.

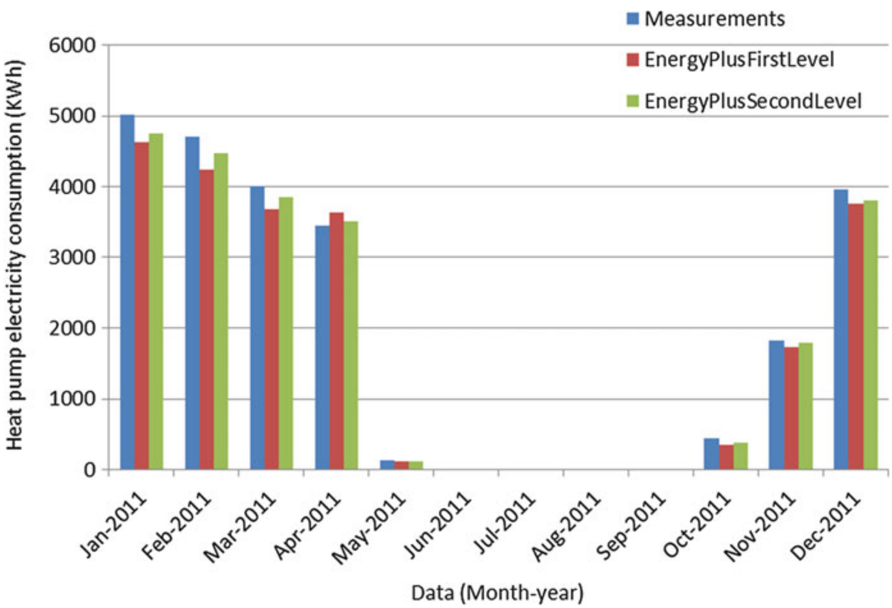
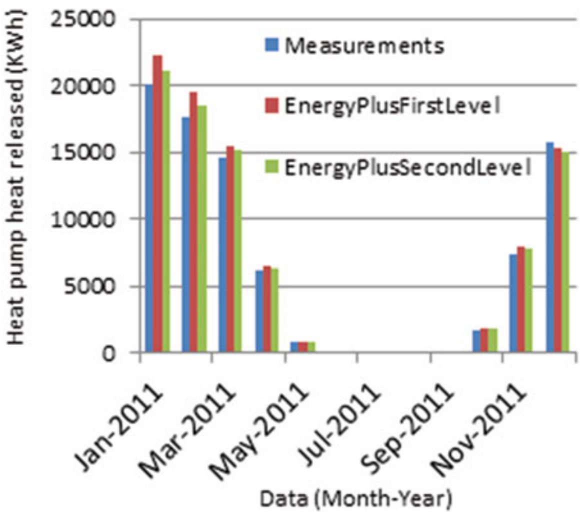


Fig. 34.4 Monthly heat pump electricity usage

Fig. 34.5 Monthly heat pump heat released



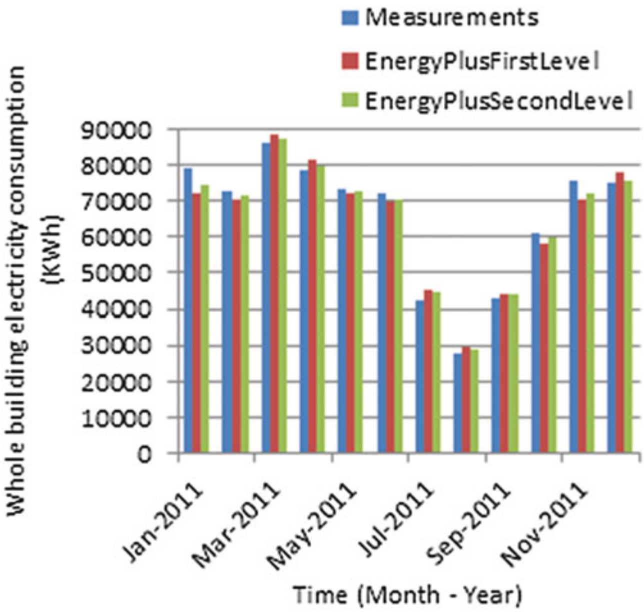


Fig. 34.6 Monthly whole-building electricity usage

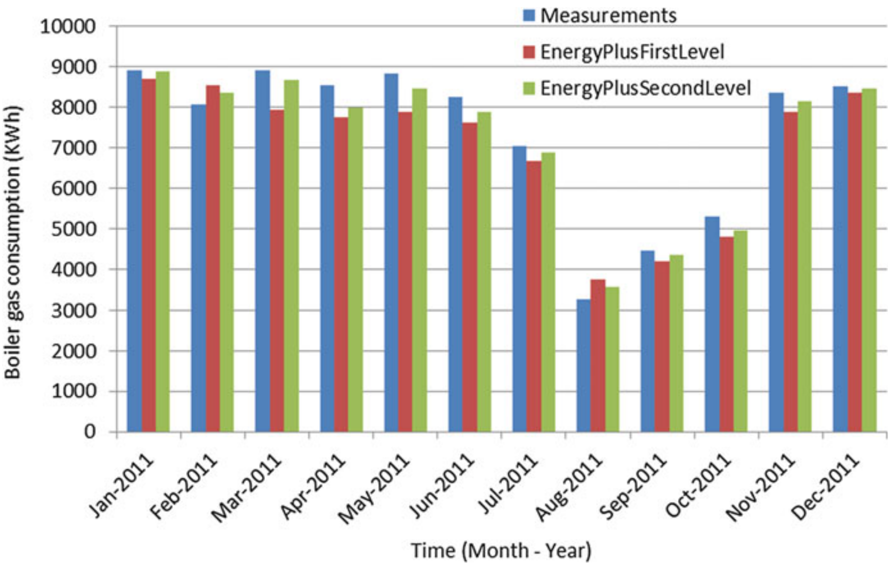


Fig. 34.7 Monthly boiler gas consumption

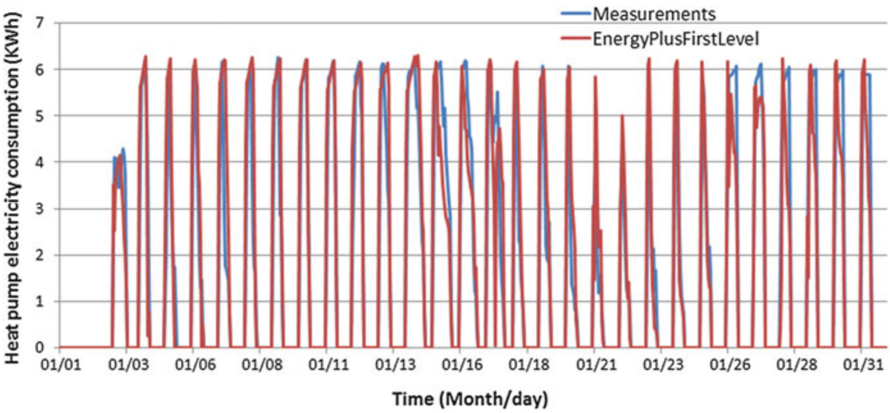


Fig. 34.8 Hourly heat pump electricity consumption

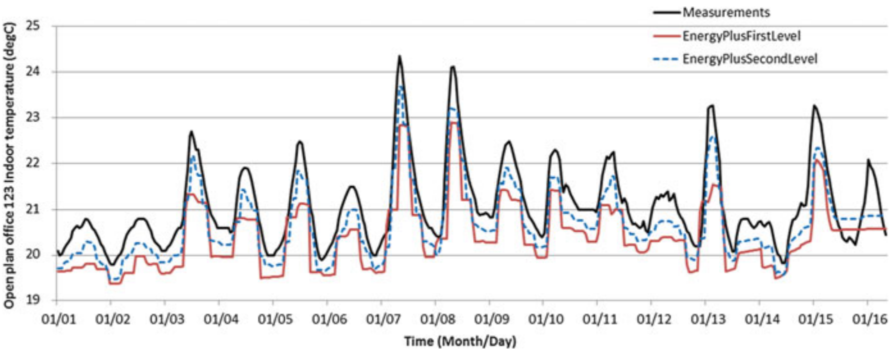


Fig. 34.9 Hourly open office first floor 1.23 indoor temperature comparison – over 2 weeks of data

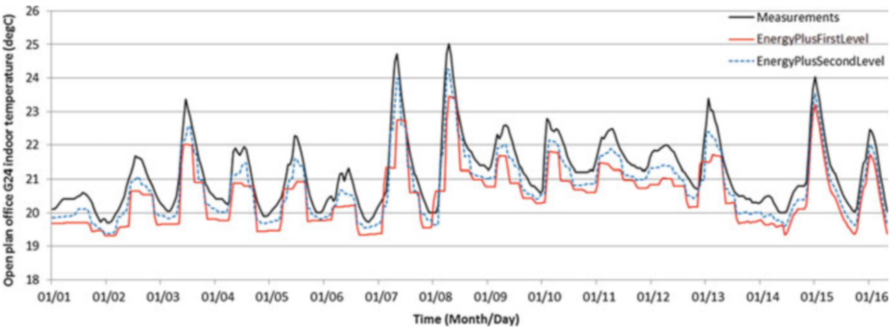


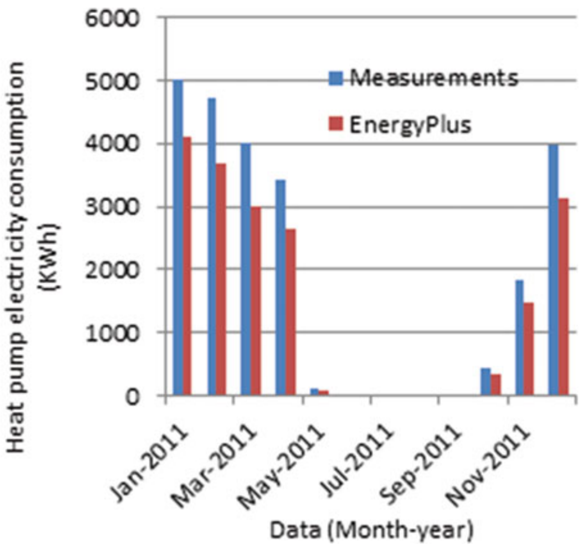
Fig. 34.10 Hourly open office ground floor G24 indoor temperature comparison – over 2 weeks of data

4.2 Energy-Saving Opportunities

Following completion of the calibration process, further reductions in energy consumption could be made by modifying the time schedule of the heat pump. The floor material structure is a concrete base and has a thickness of 70 cm. Therefore, each floor presents a slow thermal response. The time during which the heat pump is turned on can vary between 6 and 12 h and depends on weather conditions. This is managed by the building management system (BMS) technician, who, on the basis of experience and the weather forecast, decides in advance how many hours it will be turned on during the following week. Consequently, the ON/OFF time schedule of the heat pump (which supplies 80 % of the building's heat) is not regulated efficiently because it is not based on real weather condition and the thermal behaviour of the building. Its electricity consumption is higher compared to what is required to provide optimal thermal conditions throughout the building.

Alternatively, the present research analysis used EnergyPlus to turn the heat pump on and off based on the real thermal behaviour of the building and weather conditions given by the weather data file. Results showed that the time required to keep the heat pump on varied from 4 to 8 h at night in order to maintain satisfactory comfort conditions inside the building. Consequently, less time is required compared to that managed by the technician on the BEMS (from 6 to 12 h). Figure 34.11 presents the heat pump's measured and EnergyPlus model output monthly electricity consumption. It was verified that energy savings varied between 20 and 27 % on a monthly basis. Figure 34.12 shows a comparison between measurements and model outputs related to the heat pump's heat released, where from 5 to 10 % less heat is released compared to the measured values.

Fig. 34.11 Monthly heat pump electricity saved



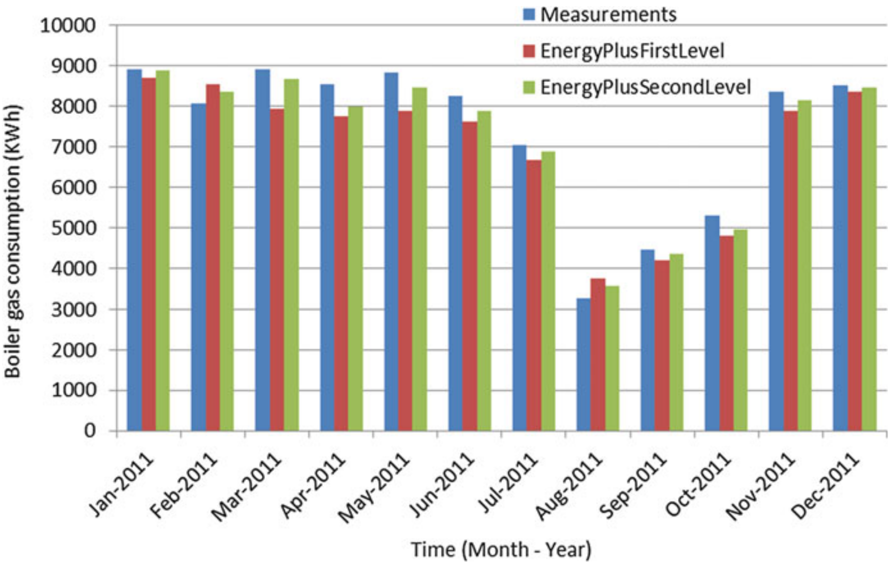


Fig. 34.12 Monthly heat pump heat saved

5 Conclusions and Future Works

This chapter presented a methodology for calibrating the hourly electricity consumption of a water-to-water heat pump. After the second level of the calibration process, the ASHRAE Guideline 14-2002 [10] is almost satisfied except for just a few cases. The second part of this research presented the required actions to improve electricity consumption related to the water-to-water heat pump. The savings from heat pump electricity consumption varied between 20 and 27 % on a monthly basis. Future research and the development of building energy modelling tools will need to focus on improving software capabilities to accept inputs based on accurate/realistic schedules for occupancy, electrical lighting use and equipment use. These inputs are highly variable in actual building use.

There is also lack of sufficient research in developing methods capable of supporting a risk analysis of investment decisions in energy upgrades of buildings, and this could represent an area of future improvement.

References

1. Perez-Lombard L, Ortiz J, Pout C (2008) A review on buildings energy consumption information. Energy Build 40:394–398
2. Directive 2010/31/EU of the European Parliament and of the Council. On the energy performance of buildings. Articles 14–16, 19 May 2010

3. Raftery P, Keane M, Costa A (2011) Calibrating whole building energy models: detailed case study using hourly measured data. Energy Build 43:3666–3679
4. Bertagnolio S (2012) Evidence based model calibration for efficient building energy services. Ph.D. Thesis, University of Liège
5. Menezes AC, Cripps A, Bouchlaghem D, Buswell R (2012) Predicted vs. actual energy performance of non-domestic buildings: using post-occupancy evaluation data to reduce the performance gap. Appl Energy 97:355–364
6. Liu G, Liu M (2012) A rapid calibration procedure and case study for simplified simulation models of commonly used HVAC systems. Build Environ 46:409–420
7. CarbonBuzz-website. http://www.carbonbuzz.org
8. Hamilton I, Steadman P, Bruhns H (2011) CarbonBuzz—energy data audit, UCL Energy Institute, July 2011
9. EnergyPlus Version 8.2 (2014) U.S. Department of Energy, Energy Efficiency and Renewable Energy, Office of Building Technologies. http://www.energyplus.gov
10. ASHRAE guideline 14 (2002) Measurement of energy and demand savings. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA
11. Mustafaraj G, Marini D, Costa A, Keane M (2014) Model calibration for building energy efficiency simulation. Appl Energy 130:72–85
12. Azar E, Menassa C (2012) A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. Energy Build 55:841–853
13. Morris M (1991) Factorial sampling plans for preliminary computational experiments. Technometrics 33:161–174
14. De Wit S, Augenbroe G (2002) Analysis of uncertainty in building design evaluations and its implications. Energy Build 34:951–958
15. Heiselberg P, Brohus PH (2007) Application of sensitivity analysis in design of sustainable buildings. Proceedings of the international conference on sustainable development in building and environment, Chongqing, China
16. DesignBuilder. www.designbuildersoftware.com
17. CIBSE Guide (2006) A environmental design. The Chartered Institution of Building Services Engineers, London
18. ASHRAE Fundamentals Handbook (2005) Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc
19. ASHRAE Standard 62.2 (2013) Ventilation and acceptable indoor air quality in low-rise residential buildings