

MODELLING AND MONITORING SUMMER PERFORMANCE OF BEAUFORT COURT

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ABSTRACT

This paper reports a study of a unique system that integrates many renewable energy resources to achieve zero CO₂ emission for building services for the head office of a company specialised in renewable energies. A dynamic thermal model was developed to simulate the summer cooling using both design criteria and recorded data. The monitored data acquired by the Building Management System (BMS) were also analysed with the predicted results to assess thermal performance of the system. It was concluded that the cooling was adequate for most of the time during moderate summer conditions but could be insufficient when extreme heat occurs such as in 2006. The current operation of the system could be modified to improve cooling quality, including automatic control of the building's ridge lights to allow heat to escape and to use night cooling.

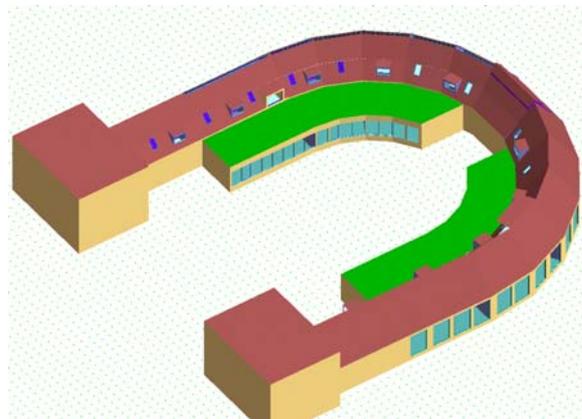
KEYWORDS

Dynamic thermal modelling, Building management system (BMS), cooling system, stratification, monitoring

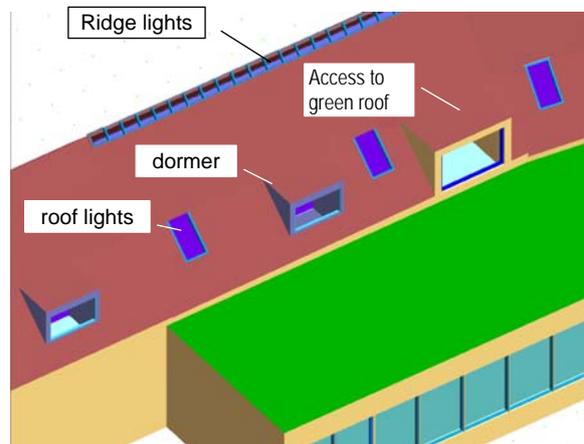
INTRODUCTION

As the headquarters of Renewable Energy Systems, Beaufort Court naturally has many sustainable features to match its owner's initiative and engagement in sustainable development, including renovation of a rural farm building into a high standard modern office, widespread use of clean and renewable energy and a high degree of integration and control over various services systems (Figure 1). Its uniqueness and complexity can be seen as follows. Firstly the building is refurbished old farm house with unique architectural features that deserve preservation. The unique shape and complex geometry make calculation of heating and cooling loads difficult. Difficulty also includes uncertainty of thermal properties of the old materials in the building envelope. All these result inevitably in discrepancy between the theoretical calculation and real monitoring. Secondly the system integrated many new technologies, from various renewable heating technologies such as solar and PV heat collectors and a biomass boiler, to cooling by groundwater from a borehole. The integration is also designed to maximise the use of renewable resources with

complement for thermal environment quality by additional heat supply from natural gas boilers. Such requirement adds complexity to the system control. Thirdly a Building Management System (BMS) after commissioning normally needs tuning for correction of faults, satisfaction of occupants and optimisation of operation. Only then is it possible to achieve the design goals.



a) the whole perspective view



b) The details: the ridge lights, roof lights, dormer windows and door on the slope roof

Figure 1 Some physical features of the thermal dynamic model of the building

The cooling system was sized using dynamic thermal modelling and operated with a BMS to achieve a highly automatically controlled indoor environment and low CO₂ emissions. Having been operating over three years, the performance of the cooling system was examined closely using monitored data recorded by the BMS and a specially developed thermal model.

The main objective of this study is to examine how closely the computer modelling corresponds to the actual monitored performance. By looking at the input data for the model, results interpretation, and predicted thermal details, this study will focus on how thermal modelling could be applied properly to assist to optimise environmental design, which covers indoor comfort and energy efficiency. Also discussed are the challenges that the modelling encountered, including dynamic response of ridge lights that control night cooling in summer, the curved sloping roofs of the original farm building, and stratification during summer cooling.

The system has been up running since 2004. It has been operated over three summers, including 2006 when extreme high temperatures were recorded for the outdoor air and many complaints raised. This investigation was to find out thermal performance of the cooling system and the building by analyzing the monitored data acquired by the BMS and a specially developed dynamical thermal modelling exercise.

This report firstly summarises the original design briefs to provide a background standard for this assessment and outlines the cooling strategy and system control are outlined to lay a base for the data analysis and discussions. Then it describes the methodology developed to carry out the heating assessment, which consists of three parts; first the criteria developed specially for this assessment exercise; theoretical assessment; second the recorded values of selected variables. Finally it presents the analysis and discussions. The conclusion is in the final section.

METHODS

There are a number of methods to assess the performance of the cooling system. In this study the methods consist of the following elements:

- Selection of the worst outdoor conditions, and the worst space within the building;
- Selection of the variables to assess indoor quality and of the typical rooms to be representative of the whole building.
- Selection of sensors of the BMS that provide key information of the heating operation.

The cooling system

The design criteria for the indoor thermal environment were set to meet the requirements: the resultant temperature should not exceed 25 °C more than 5% of the year and not exceed 28 °C more than 1% of the year, in equivalent, of 117 and 23 hours respectively(DETR,).

Three air handling units provide 2500 l/s serviced air to the working spaces at 15 °C during the cooling seasons. The cooling water is from boreholes about 80 m below ground level and runs into the coils in AHUs. The water temperature is about 12 °C and return is expected to be at 17 °C. This 5 K expected rise would provide 105 kW free cooling when the pump is running at 18 m³ per hour.

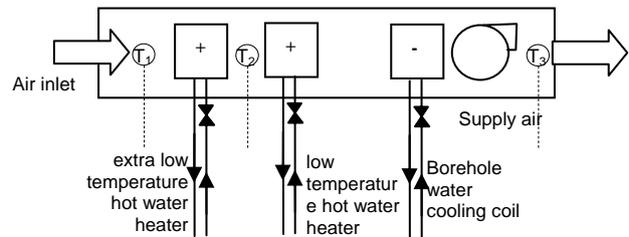


Figure 2 The air handling unit

In addition to the cooled air supply, the local convectors provided additional cooling when it was needed. The design cooling load was to be 10W/m²

The control

Both the AHUs and borehole water pump was initially from set to run for 7:00-22:00 (MF 2001) in design but now for 7:45-20:00.

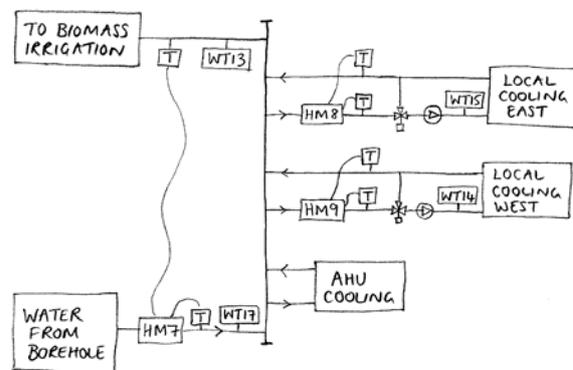


Figure 3 schematic diagram of the cooling control

The cooling and control are operated by the BMS, designed by Trend Controls, and installed by DWEC. The system also integrates the ridge lights system and the heating system that uses hot water from three sources: gas boilers, biomass boiler and solar heat collectors.

The dynamic thermal model

The dynamic thermal model was created using TAS, which was also the tool used to size the cooling at the design stage(EDSL, 2004). TAS allows very complex geometry to be built and precisely calculates accordingly each item of heat exchange and transfer such as solar shading and penetration, convection, radiation and so on.

Figure 4 shows the two floors in east wing as an example. Each space in the building was defined as one zone where casual gains, air conditions, convector cooling and air supply were specified with one value for each of the variables.

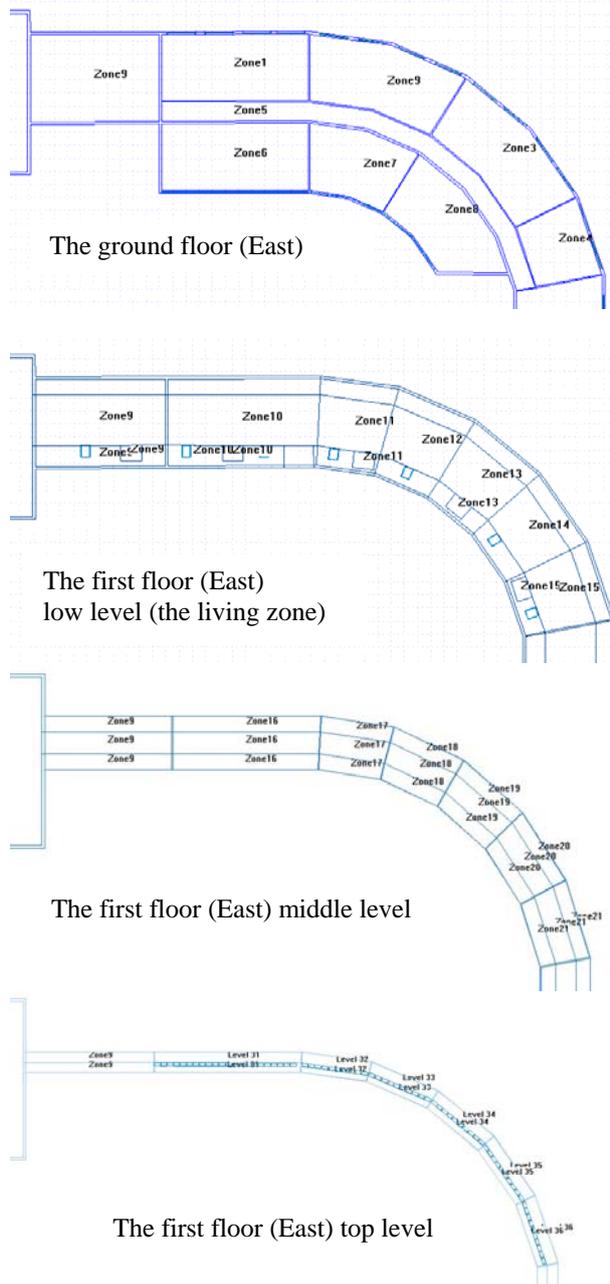


Figure 4 Plans of the four levels in the model

To calculate stratification, the first floor was further divided into three levels, and horizontally the open plan office was divided into size zones, so that the environmental variables, such as air temperature, mean radiant temperature, pressure and so on were calculated in 18 locations over this space large space. Therefore the air movement and temperature distribution could be computed.

The ten dormer windows and two doors all on the two slope roofs were explicitly modelled so that heat transfer through all of their surfaces, from transparent to opaque were all accurately calculated. It has to be pointed out that the model simplified the roofs of the dormers as flat ones, as the effects of such approximation was negligible due to the main heat gains via the dormers were from the transparent windows and not from the well insulated roofs.

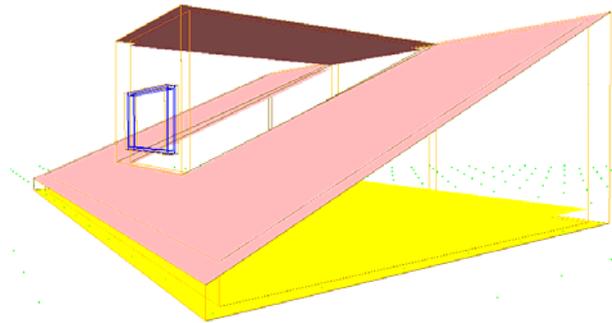


Figure 5 details of the dormer windows in the model

Thermal properties

The actually figures for thermal properties of all building elements used in this modelling were from manufacturers data sheets, they summarised in Table 1.

Building elements	U-value	manufacture r
External wall	0.32	Rockwool
Internal wall	-	
Pitched roof	0.31	Rockwool
Green roof	0.30	Rockwool
Ground floor ceiling	-	
Ground floor	0.52	
windows Steel framed	2.2	Crittall
Ridge & roof lights (VITRAL F58-2)	1.6	Velux
Ground Floor External façade	1.2	Velfac

(6-12-6, clear, supper low E Toughened, Argon)

Table 1 the key building elements

Internal conditions

In the office spaces, the occupancy: 9:00 - 18:00, and heating/cooling, 7:00 – 20:00, weekdays. It is weatherwhile of mentioning that in real life people work more flexible working hours than this suggests. Casual gains were: 10 W/m² for occupants, 8 W/m²; lighting and 15 W/m²; Electrical equipment:

Outdoor conditions

From the monitored data, it was found that July 2006 was extremely hot. Therefore this month was selected for this assessment to see the capacity of the system. In particular the 3rd week had five consecutive days of clear sky and the data of this week were analysed

For computer modelling, two sets of data were used. Firstly the real recorded out air temperatures were used for simulation, so that the predicted results could be compared against the monitored ones.

Secondly the standard weather data, the **Test Reference Year** (TRY) for Kew, a real hourly weather data for a year that takes into account of statistical the local weather variations. As each hourly figure of a variable in TRS is an average value over 10 years at the hour, this “statistical” year are normally more moderate than a particular year.

For this typical one day modelling of thermal response to the changes of weather, the program starts from 10 preceding days to count to pre-condition the building. This allows for the temperatures of the building fabric to stabilise.

RESULTS AND DISCUSSION

The real operation

Figure 1 shows a typical week in July 2006, the hottest month that had been recorded by the BMS. During the five working days, both the outdoor and average indoor air temperatures were plotted in parallel, which was expected to reveal cooling quality of the system. The temperatures of the chilled water are also plotted. The difference would show the cooling effect. The light blue line represents working status of the local convectors, “0” is local cooling with the convectors.

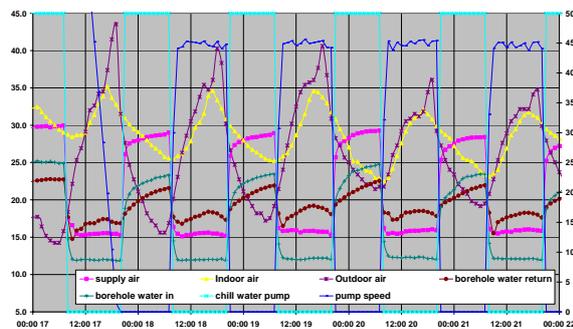


Figure 6 typical week operation

The recorded readings for the outdoor air temperature seemed extremely high compared with the data provided the commercial weather station nearby. There were a few weeks the ambient temperature went over 40 °C, but this was not shown in the data at a nearby station (Figure 7).

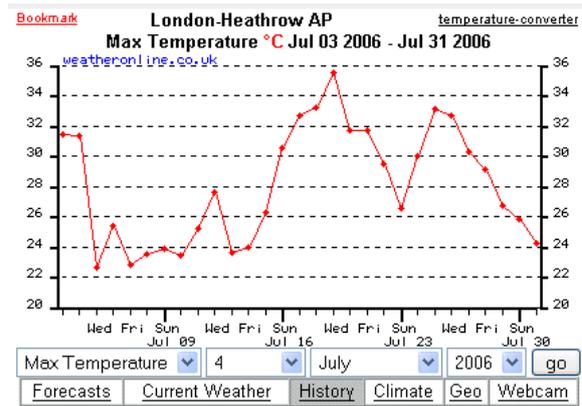


Figure 7 Ambient temperature from a commercial weather station (Weatheronline)

The summer of 2006 was indeed extremely hot. To confirm the measurement was correct, both sensors were examined, the one near solar panel outside and the one inside AHU2 when it was running. Both gave consistent readings. Therefore these data were considered correct and used for all analysis in this paper.

The recorded temperatures for the supply air, borehole water and return water were all rising during the off work hours when the AHU fan stopped. This indicates that there was a huge heat built up during the day inside the plant room.

During some of the early mornings, the indoor environment was over 7-9 K hotter than outside. This suggests that night cooling could be applied to cool the interior spaces of the building. Although the ridge-lights, controlled by BMS, were open during all clear days, the airflow did not seem to remove the indoor heat easily. The main reason can be that there were no other openings on ground level to allow outdoor airflow coming, following the stack effect and escaping through the ridge-lights.

The borehole water pump was running in full power during the working hours from 9:00 till 20:00, which indicated a high cooling demand during these days (the blue line in Figure 6). The local convectors started running in full power 7:45 and finished at 20:00 (light blue line, 0%=full cooling status, 50%=none; 100%=full heating).

The monitored results show that the indoor thermal conditions did not satisfy the design criteria: in July alone, there were 55 hours the indoor temperature exceeded 28 °C during the 9:00-18:00 on the working days. This was for not fully occupied internal conditions. The next modelling shows that with a full occupancy, the situation would be even worse.

Comparison between the modelled and monitored results

It is widely accepted that there will be discrepancy between modelling and reality. Beaufort Court is such a complex system and there are much uncertainties involved. It will be unrealistic to assume the modelling will be 100% accurate. Historically modelling at the design stage has been used for sizing and provide general understand and estimation on those variables of interests.

The comparison was made in two typical days in the hottest month, one was a clear day whilst the other; overcast.

During the clear day, the calculated temperature agrees very well with the actual recorded one, not only the varying pattern but also the actual hourly values (Figure 1).

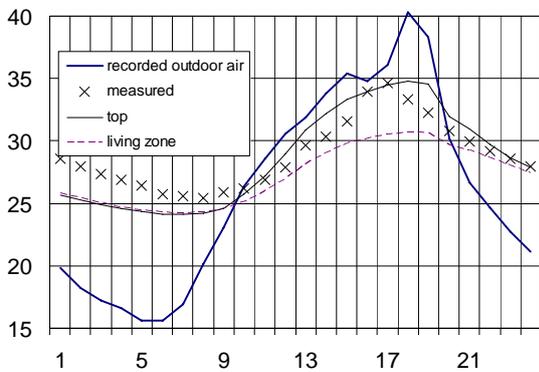


Figure 8 Comparison between model prediction and BMS monitored results (Clear day)

The overcast day was slightly disappointing. Firstly the actually monitored one was rather stable, which no much change, within 1.5 K diurnal variation, in air temperature throughout the 24 hours. The predicted however shows large fluctuation. The hourly values predicted were always higher than the measured. However the discrepancy was about 2 K.

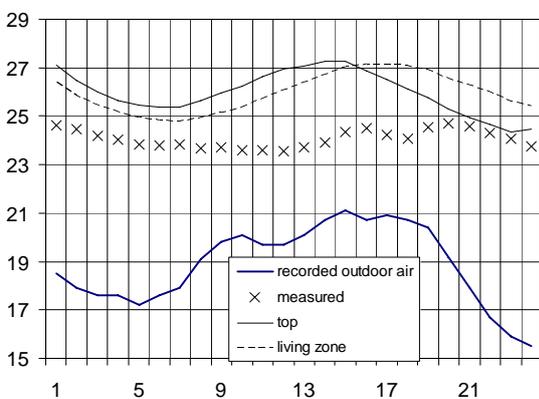


Figure 9 Comparison between model prediction and BMS monitored results (an overcast day)

The main cause for such discrepancy was from the uncertainty of the actual values used in the system. This includes, the flow rate of supply air, and the local cooling loads. These two variables were not recorded in BMS, therefore it is really difficult to access the accuracy of the model.

Secondly the space was only about 30% occupied, but 100% occupancy was assumed in the modelling, as this would reflect the worse scenario when it was fully occupied. This additional heat in the model was significant during the overcast day and less important in the clear day when solar penetration was the dominant source in the indoor heat gains.

Finally the internal casual gains in the model also included lighting, which did not reflect the actual situation. During a sunny day all luminaries were switched off by their own automatic system that detected luminance at the desk level.

Overall this model was still considered valuable as it responses correctly with changes air infiltration and heat gains that created stratification. This provides sufficient grounds for comparison studies to assess various options of system operation, such as the effects of opening ridge lights on the building roof.

Indoor thermal conditions

The modelling with real weather data confirmed that the cooling was sufficient for a mild weather, typically characterised by the TRY weather described above. The main concern is, however, very often a particular year the summer can be much more hotter than that of the TRY data. 2006 shows clearly that the summer was much hotter than average and both the monitored and model data confirmed the cooling was insufficient. Thermal discomfort would deteriorate when the space is fully occupied.

Effects of the ridge lights

Opening the ridge lights can allow heat to escape and hence could be an effective way of avoid overheating in the upper space in the first floor. On the other hand, the incoming air due to the wind could mix the hot air at the high level with the cool air in living area, and result in warmer air in the living area

Three modes of operation were simulated using the DTM, ridge lights closed, open, and open only during the night (night cooling) and results are shown in the air temperature at two levels, the top and living area

It is clear that when the ridge lights were closed, there was a strong stratification which created a large temperature difference between that at the living area and that of the top (Figure 10: solid circles: closed).

The high temperature at the top could result in high resultant temperature and cause discomfort. This was not calculated in the modelling as the space was divided vertically into three levels, and the mean radiant temperature which accounts on surfaces that enclose a zone could not be calculated properly. Some of the occupants were already using white cardboards placing at the ceiling level to block excessive solar light, and this actually reduced the mean radiant temperature at the living area, which was really a practical and effective way to improve thermal environment in the living area.

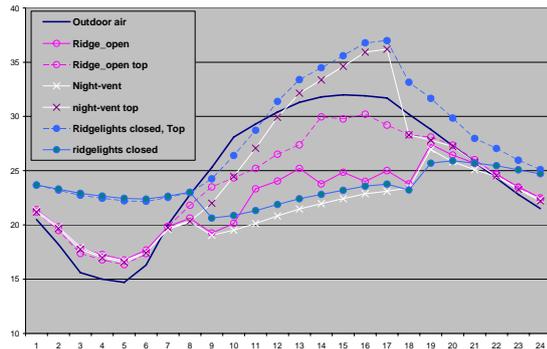


Figure 10 air temperature at two levels in the top floor under three ridge lights conditions

When the ridge lights were open, the heat at the top could escape (Figure 1: open circles). This was proved by examining the hourly air flow through the ridge lights. However there was irregular incoming wind entering the building through these ridge lights and it mixed the indoor air and reduced the temperature difference. Although the air temperature at the living area was higher than when the lights were closed, the mean resultant temperature could be lower which is preferable. In addition, the unexpected air movement could be a positive and desirable feature of air conditioning in modern office buildings.

Night cooling has been proved in many cases and recommended as effective measure to reduce cooling loads during the occupied hours. This measure did have some effects for this lightweight building (Figure 1: the lines with crosses). Firstly the temperature during the night was low so that the indoor space, the heat absorbed by the furniture, wall surfaces and so on could be released back into the air and brought away by the natural ventilation. Even during the day, the temperature at the living area was constantly 1~3 K lower than if the ridge lights had been closed whole day. The largest difference, as expected, happened at the first few hours of the day. Naturally the initial cooling loads would be significantly reduced. Further study is needed to quantify this saving for optimising the operation of the system to minimise the energy demand.

All ridge lights in this study were modelled either 100% open or completely shut. The model was actually made possible to examine the effects of opening the roof lights a certain percentage. This would be worthwhile of further study and develop a better operation strategy of the BMS.

CONCLUSION

Both the monitored and model data confirmed the cooling was insufficient. Thermal discomfort in the top floor was alarmingly high and remain so for a whole afternoon. Although the summer 2006 was rather extreme, it provided a good opportunity to test the capacity of the system. It is felt that the system was unable to handle such excessive condition in summer. This would exacerbate if the space is fully occupied as the company grows and employs more people to work in the space.

The model developed here simulates some physical phenomena that are critical for this type of study, including stratification satisfactorily. It would be used for other simulation to explore better operation and control in future. That could include looking in the percentage of opening for the ridge lights and there program the BMS for more effective operation.

The model using the hottest day in TRY shows that indoor thermal condition was satisfactory: which confirms FM's modelling carried out for sizing the cooling loads at the design stage.

It is clear that control of the ridge lights can affect firstly the indoor thermal comfort and secondly the energy required for cooling. Integrating this into the BMS could improve the cooling performance.

The benefits of night cooling are obvious. It should be done in Beaufort Court to improve efficiency of the cooling system and save further energy.

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REFERENCES

Beaufort Court: <http://www.beaufortcourt.com/>

RES, 2004, Green Energy at Beaufort Court,
Publicity leaflet.

Crittall Windows Ltd: [http://www.crittall-
windows.co.uk/](http://www.crittall-windows.co.uk/)

DETR, Best Practice Programme, Report 30, A
Performance Specification for the Energy
Efficient Office of the Future.

DWEC Europe Ltd: <http://www.dweceurope.com/>

EDSL, 2004, TAS theory.

MaxFordham 2001, Analysis of Summertime
Temperature for Renewable Energy System new
Head Office, Kings Langley.

MaxFordham, September 2004. Final and
Publishable Technical Report

Rockwool Ltd: <http://www.rockwool.co.uk/>

Trend Control Systems Ltd: [http://www.trend-
controls.com](http://www.trend-controls.com)

Velux: <http://www.velux.co.uk/>

Weatheronline: <http://www.weatheronline.co.uk/>