MODEL-BASED CONTROL OF RENEWABLE ENERGY SYSTEMS IN BUILDINGS

Y Zhang[1], and V I Hanby[1]
[1]Institute of Energy and Sustainable Development
De Montfort University
Leicester, UK
{yizhang, vhanby}@dmu.ac.uk

ABSTRACT

The paper describes a research project which addresses the problem of supervisory control of systems which include a range of heat sources combined with active and passive thermal storage. The work is based around a prototype building which has a ventilated PV array, solar air and water heating, biomass-fired boiler and a stratified thermal store.

The supervisory control problem is, for each source, whether to deploy the energy directly into the building, store for later use or to reject to the environment. These decisions are made by a building management system programmed with a complex, arbitrary set of rules and setpoints. Analysis of the data for the early stages of building operation indicate strongly that it is unlikely that optimal use can be made of the renewable energy sources with this approach.

The existing building, plant and control system have been modeled using a commercial simulation environment and calibrated against measured data from the building. Examination of the operation of the existing control scheme has shown that significant improvements are possible. The next stage of the work will be to deploy dynamic optimization methods to update the supervisory control decisions at fifteen minute intervals during the day.

INTRODUCTION

This on-going research project addresses the issue of the control of renewable systems in buildings. Renewable energy sources are generally of low intensity and temporally inconsistent: these characteristics cause particular control problems which must be solved if the integration of renewable energy into buildings is to be effectively exploited. The overall objective of a successful control system must be to maximize the use of renewable energy sources and to minimize the import of external energy, subject to constraints such as the maintenance of satisfactory internal conditions.

To achieve this objective, a top-level supervisory control is necessary. The supervisory control must be able to monitor the states and demands in the system, and adjust control variables (setpoints and actuators) accordingly to suit the dynamics of the system.

This requires two aspects of the system to be studied: the dynamic interaction of renewable energy systems with the building in order to understand the behaviour of the complete system and an effective methodology for implementing dynamic optimized control.

In the following sections of this paper, the building and the renewable system at the Brockshill Environment Centre are introduced. The development of the dynamic models of is described. We then discuss the behaviour of the present BEMS control strategies, and indicate that it has limitations which offer potential for improvement if it were to be replaced with a control strategy which was able to adapt to the changing environment.

BROCKS HILL ENVIRONMENT CENTRE

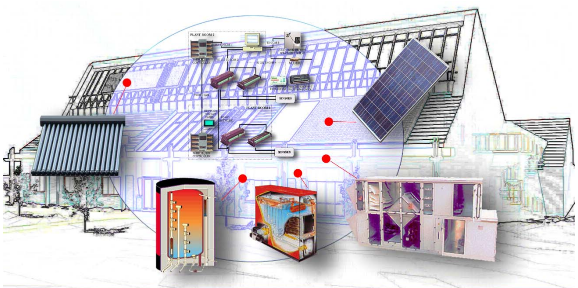

Figure 1 Brockshill Environment Centre

The Brocks Hill Environment Centre (Cartmell, 2004), is the centre-piece of the Brocks Hill country park in the city of Leicester, UK. The design of the building reflects the considerations of daylight penetration, natural ventilation and the use of solar radiation for wintertime space heating. The building has also been designed to be thermally massive as well as being insulated to a much higher standard than the requirements of the present UK Building Regulations. These energy-conscious features make the building itself an interesting subject for dynamic thermal modeling of the building and its systems.

The thermal systems in the building make use of renewable energy from solar air and water heating, and from burning biomass collected from the surrounding woodland. A $20m^2$ evacuated tube solar water collector (SW), and a total of $36.2m^2$ ventilated photovotaic array and solar air collector (VPV/SA) are installed, together with a 19kW dual-fuel boiler. At the centre of the system, a 1000 litre stratified hot water storage tank is used as a hub connecting all circuits. Heated water from the boiler, the solar water collector, and the solar air collector heat exchanger, are stored in the tank, which supplies a heater battery in the air-handling unit and a separate domestic hot water cylinder.

The internal space of the building has been divided into three heating zones: the exhibition hall, the classroom, and the restaurant area. The heating and ventilation system consists of an air-handling unit (AHU) with a sensible heat recovery exchanger and a separate circuit for the VPV/SA collectors. The VPV/SA circuit can operate in one of the following four modes – preheating the inlet air to the AHU; a closed circulation loop transporting heat to storage via an air-water heat exchanger; open circuit cooling the PV panels, or switched off. The AHU has a supply fan, an extract fan, and a heater battery.

The operation of the whole system in controlled by a centralized building energy management system (BEMS) provided by TREND Control Systems Ltd. The control strategies were designed and commissioned in a steady-state context – the operational mode of the system is decided by a set of pre-defined setpoints. This implies that there may be potential inefficiency because the dynamics of the renewable energy systems and the building are not taken into account.

MATLAB/SIMULINK® ENVIRONMENT

The Matlab and Simulink® environment (Mathworks, 2005) has been widely used in dynamic system modeling in many engineering fields, especially where control technology is needed. The following factors were relevant to the use of these programs in this work:

- A wide range of mathematical libraries is provided. The functions are efficiently implemented, especially for matrix and array handling.
- An extensive collection of components for modeling continuous, discontinuous, and discrete systems. It is possible to build a system model using graphical components (see Figure 2). In this way, complex models are easier to understand and maintain.
- A variety of ordinary differential equation (ODE) solvers are provided for different types of system dynamics. It is possible to achieve stable solutions by choosing an appropriate solver.
- Models developed in other languages can be imported into this environment.
- A real-time interface is available for linking with control hardware.

BUILDING THERMAL MODEL

It was decided to use a simplified zone thermal model, the implementation of which is shown in Figure 2. The mathematical model was originally introduced into the UK by Crabb et al. (Crabb et al., 1987). The model has two dynamic temperature nodes roughly representing the air and a lumped structure node. Two dynamic heat balance equations are used:

$$C_a \frac{dT_a}{dt} = Q - K_i (T_a - T_w) - K_f (T_a - T_o) \quad (1)$$

$$C_w \frac{dT_w}{dt} = K_i (T_a - T_w) - K_o (T_w - T_o) \quad (2)$$

where,

T_a Air temperature (°C)

T_w Mean wall temperature (°C)

T_o Outside air temperature (°C)

Q Heat input to the air node. (kW) This has three components: the heat input to the zone via the warm air terminals (Q_i), casual gains from the occupants and electrical equipment (Q_c) and solar gain (Q_s) . See equation 3 – 6:

$$Q = Q_i + Q_c + Q_s \qquad \text{[kW]} \quad (3)$$

$$Q_i = \dot{M}_a C_p (T_s - T_a) \qquad \text{[kW]} \quad (4)$$

where,

M_a Supplied air mass flow rate (kg/s)

Cp Specific heat of air (kJ/kg/K)

T_s Supplied air temperature (°C)

The casual gain (Q_c) was treated as a constant during the occupied hours:

$$Q_c = F_c \cdot 1.0 \qquad \text{[kW]} \quad (5)$$

F_c Casual gain factor

The solar gain (Q_s) was treated as a gain factor relating the gain to the zone and global solar radiation on the horizontal:

$$Q_s = F_s I_{gh} \qquad \text{[kW]} \quad (6)$$

F_s Solar gain factor

I_{gh} Global horizontal solar insidence (kW/m^2)

The model uses five parameters:

C_a is the thermal capacity of the air in the zone, together with other fast-response elements. (kJ/K)

C_w represents the lumped thermal capacitance of the structure. (kJ/K)

K_f is the fast conductance ascribed to ventilation and elements with little thermal capacitance, e.g. windows. (kW/K)

K_i is the conductance between the air and structure nodes. (kW/K)

K_o is the conductance between the structure node and the outside air. (kW/K)

Whilst it is possible to estimate these parameters from physical data for the building, given the availability of monitoring data it was decided to obtain values for each of the three zones using a parameter identification technique.

Table 1
Heated zones in the environment centre

	EXHIBITION	CLASSROOM	RESTAURANT
Floor Area (m²)	217.9	74.0	178.6
Heated Volume (m³)	1510.7	277.6	670.0
Area of South-Facing Glazing (m²)	66.6	11.4	9.3
Glazing to Floor Area Ratio (%)	36.1%	18.8%	8.4%
Exposed Surface Area to Heated Volume Ratio (m²/m³)	0.324	0.244	0.227

Table 1 provides some basic information about the zones. The exhibition hall is the largest heated volume which also has a high ceiling. Its exposed surface area to heated volume ratio (0.324) is nearly 50% higher than that of the restaurant (0.227). The exhibition hall also has the highest glazing to floor area ratio, twice as high as the classroom, and four times that of the restaurant.

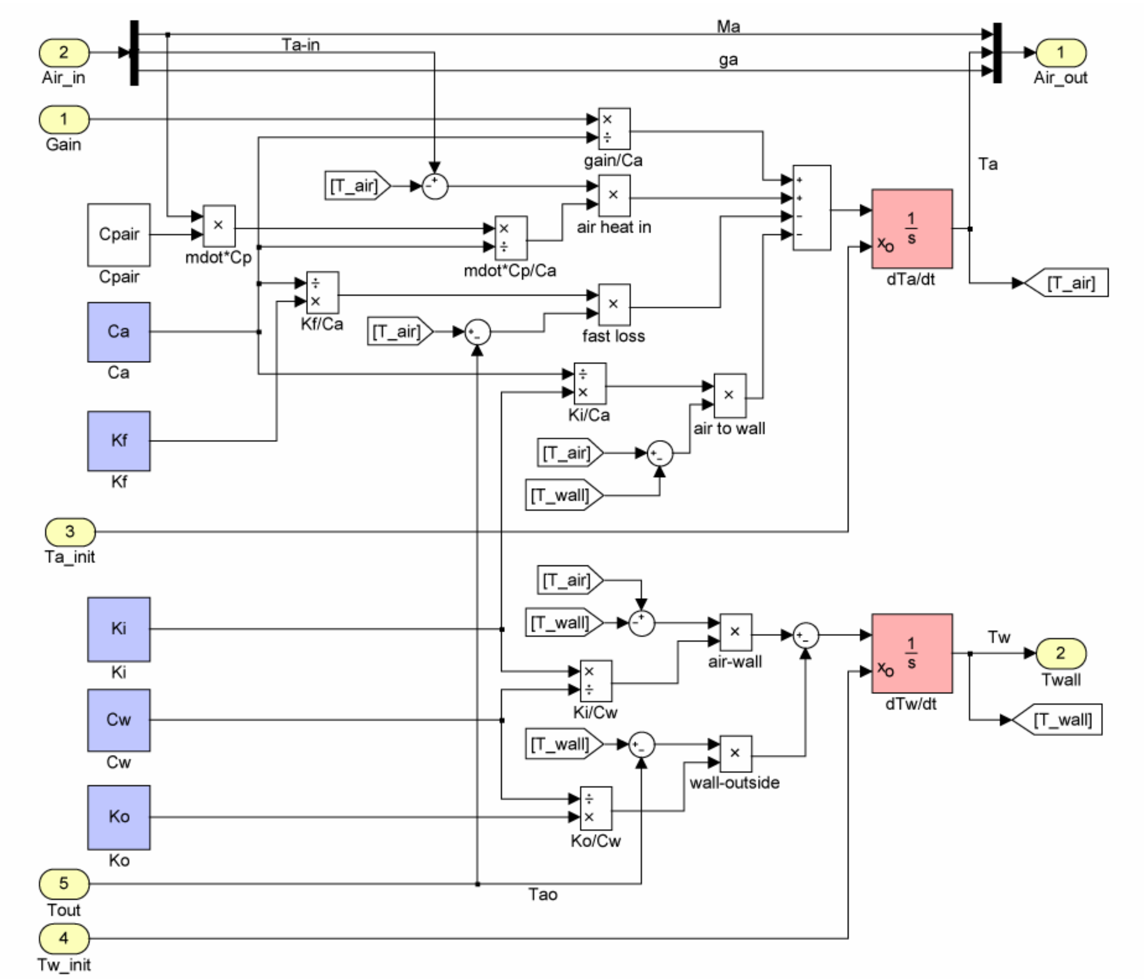

Figure 2 Simplified zone model

Monitoring data was available for the winter of 2001-2002 and was used in the parameter estimation for the three zones. Externally, the outside air dry bulb temperature and global solar radiation on the horizontal were logged; internally, the zone air temperature, supply air temperature and duct air velocity readings enabled the heat input to the zone as well as the zone air temperature to be established. However, the duct air velocity readings were found unreliable. It was decided to identified the air flow rate to each zone, as well as the solar gain factor and the casual gains factor. As a result, for each zone, there are 8 parameters, C_a, C_w, K_f, K_i, K_o, M_a, F_c and F_s, to be identified.

A constrained evolutionary strategy (Hanby et al, 2002) was used to find the values of the parameters which minimized the square of the difference between the predicted and measured zone air temperatures. Data for the month of March 2002 was selected for this purpose.

The methodology was validated by estimating the parameters for the zones from physical data, then running the model to obtain 'observed' values for the zone air temperatures. The parameter identification process should then generate values which are the same as those assumed to generate the time-series data. Repeated runs of the evolutionary strategy confirmed that in each case, the original parameters were found to an accuracy within 5% and that the zone temperature calculated to within 0.5%.

Values identified for the three zones are summarised in Table 2.

Table 2
Optimized zone model parameters

	EXHIBITION	CLASSROOM	RESTAURANT
Ca (kJ/K)	5.74E+04	2.81E+04	7.76E+04
Cw (kJ/K)	8.51E+04	1.62E+05	3.63E+06
Kf (kW/K)	0.164	0.236	0.042
Ki (kW/K)	5.423	3.845	0.411
Ko (kW/K)	0.143	0.115	0.001
Ma (kg/s)	0.641	0.750	0.774
Fc (1)	0.85	4.80	2.07
Fs (1)	15.06	15.10	8.72

It is of interest to note that the model is rather insensitive to values of C_w and K_i in the region where their values are greater than the optimum.

General agreement between the predicted zone air temperatures and those logged by the BEMS was obtained for all of the three zones, as illustrated by Fig 3. Bigger discrepancy (up to 2 °C), however, is observed in some days. Detailed examination of the data suggests that several factors could contribute to this situation and that these would be difficult to overcome in practice. These include difficulty in predicting casual gains and occupant behaviour (e.g. opening the windows).

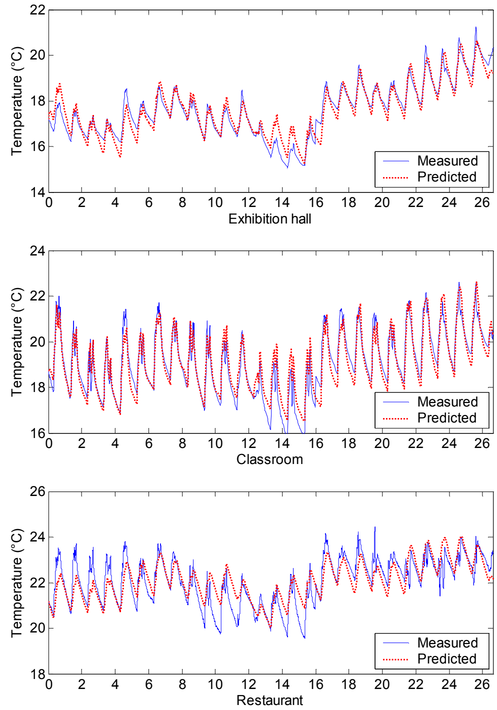

Figure 3 Observed temperatures compared with model output

BUILDING AND SYSTEM MODEL

Models for individual components in the Brocks Hill Environment Centre system have been developed. The individual components are joined together with air flows, water flows, and signals, to form the complete system.

The system model can be divided into four modules, as shown in figure 4. The Air system module contains ventilated PV panels, solar air collectors, an air-to-air heat exchanger for heat recovery, an air-to-water heat exchanger for collecting heat from solar panels, an heating battery, fans, dampers, ducts, and the three zones.

The water system module contains a boiler, evacuated tube solar water collector, a stratified hot water storage tank, domestic hot water storage tank and pumps, valves, and pipework. The water system module is coupled with the air system module via the air-water heat exchanger, and the heater battery.

The BEMS Control module closely emulates the functions of the control system installed in the building. The controller takes values from the

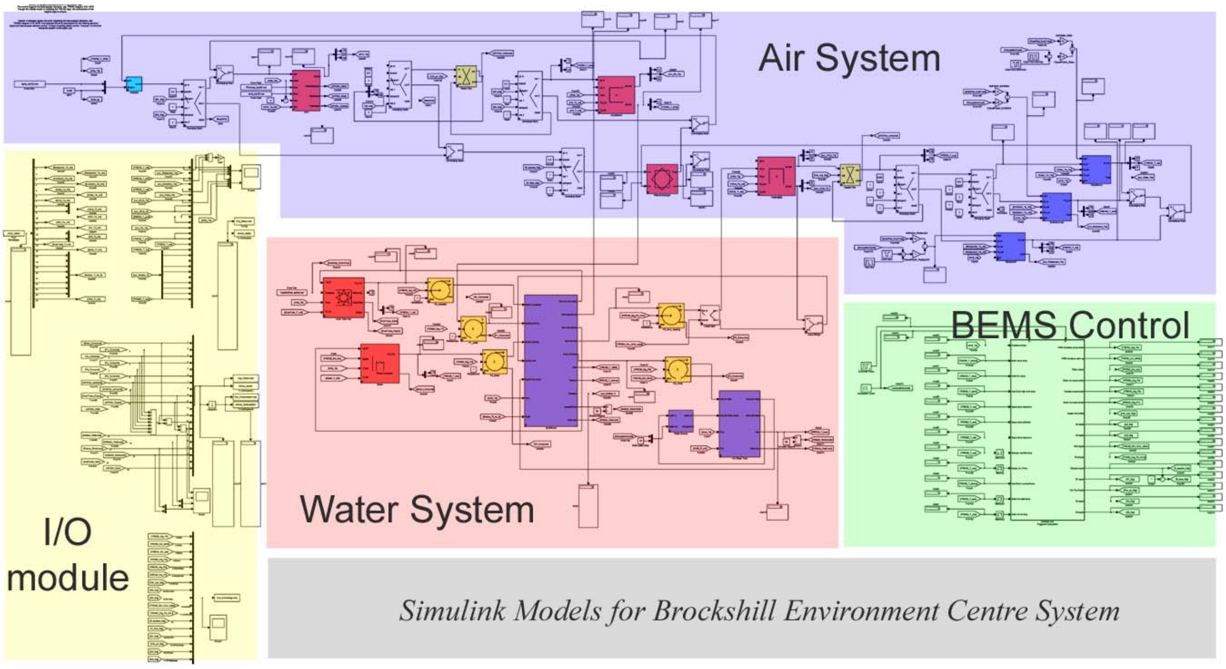

Figure 4 Brocks Hill system model

environment and the system, and is connected to the motorized dampers, valves, fans, pumps, and the boiler.

Finally, there is an I/O module in the system model. This module sets simulation parameters, initializes state variables, and gathers outputs.

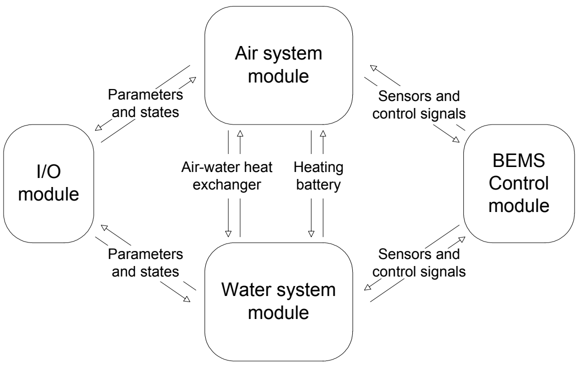

Figure 5 Interaction between modules

Figure 5 shows the interaction between the 4 modules. The air system module are connected with the water system module by two return water flows. The BEMS control module is interacting with the air system and the water system by sending control signals and reading the sensors. The I/O module is the meta-model that controls the process of simulation.

BEMS CONTROL STRATEGIES

The default control strategy implemented in the BEMS system, was based on a set of predefined rules and setpoints devised by the design engineer. By coordinating the operation of the dampers and fans, four operational modes are available for the air system:

1. VPV preheating – when there is heating demand, and there is useful heat from the VPV panels, the outside air is first directed into the VPV, before fed to the AHU.
2. VPV storing – when there is NOT heating demand, and there is useful heat from the VPV panels, and also there is available capacity in the storage tank, the air in the VPV is circulated in closed loop, and the solar heat is collected and stored in the tank using an air-water heat exchanger.
3. VPV venting – in case there is excess heat in the VPV panels (temperature exceeding 80°C), and there is neither heating demand, nor available storage capacity, the VPV is actively ventilated.
4. VPV bypass – for all other conditions, the VPV is bypassed and the outside air is directly supplied to the AHU.

The operation of the boiler is determined by the presence of heating demand in the zones, and the high-level temperature of the storage tank. The boiler and the associated pumps are only switched on when there is heating demand, and the high-level temperature in the tank is lower than 45°C. Once switched on, however, the boiler will keep running until the high-level temperature of the tank reaches 60°C.

The deployment of the evacuated tube collectors starts when temperature in the manifold is 10°C higher than the low level temperature of the stratified storage tank and stops when either the manifold temperature is equal to the low level temperature, or when the high level temperature of the tank reaches 60°C.

The present BEMS control strategy has been modeled. Recorded weather data from April 2002 was used to simulate the operation of the system. Figure 6 shows the control signals in the system, for the first 5 days in the simulation. Figure 7 shows the outside air temperature and the temperatures in the classroom, during the 5 day period.

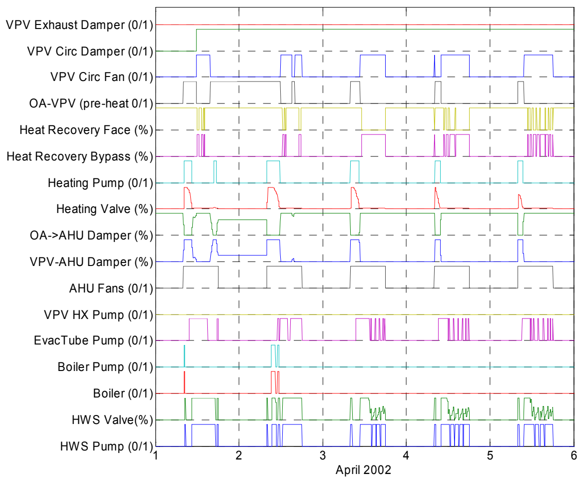

Figure 6 Simulated control sequences

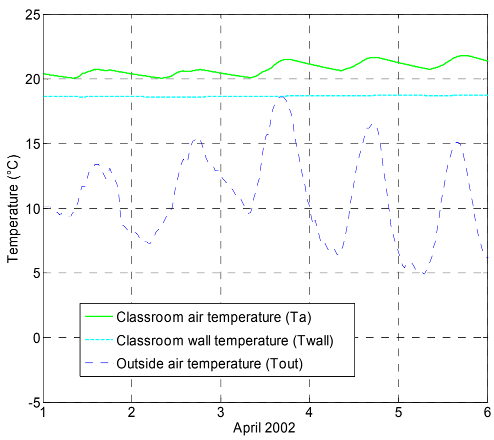

Figure 7 Classroom and outside temperatures

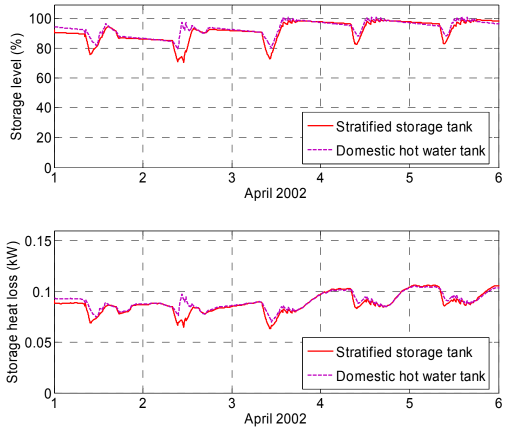

Figure 8 Storage and hot water tank operation

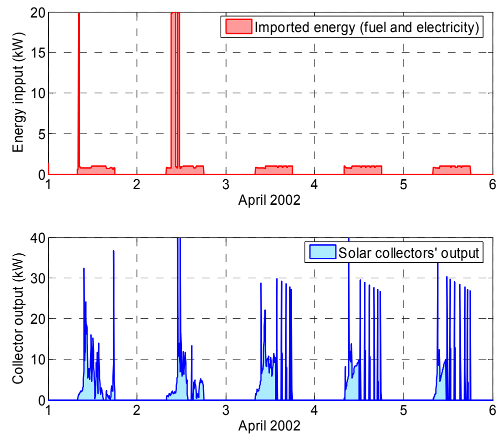

Figure 9 Energy consumption and gains

It can be seen that the outside temperature was mild during the simulation period; hence the boiler was only required to operate briefly on the morning of the first and second day. Meanwhile, the VPV and the evacuated tube collector were able to charge the storage tank. As a result, the storage level of the tanks was maintained in the following 3 days with the boiler switched off. (See Figure 8)

Figure 9 shows the fuel and electricity consumption and the collector outputs. It is noticeable that, in the day 3, 4, and 5, the solar collectors were operating intermittently, discarding potentially useful solar gains. An experiment was thus set up to test if the default control strategy could be improved. Adjustments to the set points which triggered boiler firing were made such that the boiler was not in operation during the 5 days.

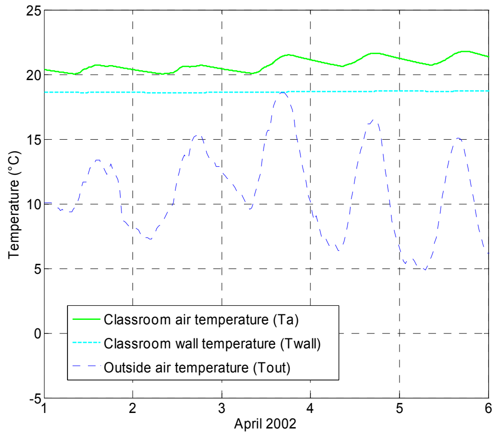

Figure 10 Classroom temperature with boiler disabled

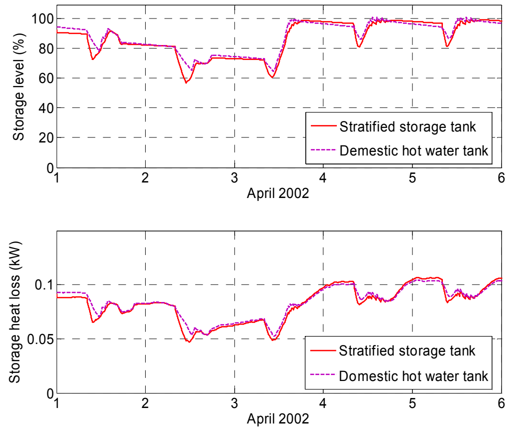

Figure 11 Storage operation with boiler disabled

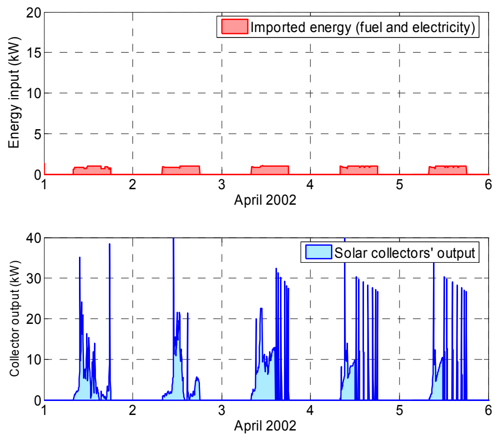

Figure 12 Consumption and gain with boiler disabled

Figure 10 – 12 shows the simulation results. Comparing the temperatures in Figure 7 and 10, the effects on the occupied spaces were barely noticeable. However, the fuel consumption by the boiler was removed (see Figure 12); and the heating demand on day 2 was met from the storage tank. The level of thermal storage was recovered later on day 3. (see Figure 11).

Table 3 summarizes the energy consumption of the system during the first 5 days of April, 2002. By modifying the boiler firing rules, a saving of nearly 46% of fuel and electricity was achieved, compared to the default control strategy. Although the pumps for the evacuated tube collector and the AHU heating battery were required to operate for longer time, which used an extra of 0.3kWh electricity, but this was offset by not using the boiler pump. As the storage temperature of the tanks was lowered between the 2nd and 3rd days, more solar heat (15% extra) was able to be collected. The lower storage tank temperature also resulted in less heat loss (7%) from the system.

Table 3
Comparison of energy balance between default control strategy and adjusted control strategy

	ITEM		BEMS CONTROL	DISABLE BOILER	CHANGE (%)
1	VPV HX Pump input	(kWh)	0.0	0.0	
2	EvacTube Pump input	(kWh)	1.3	1.4	
3	Boiler Circ Pump input	(kWh)	0.3	0.0	
4	HWS Circ Pump input	(kWh)	4.1	4.0	
5	AHU Heating Pump input	(kWh)	1.5	1.7	
6	VPV Circ Fan input	(kWh)	8.3	8.2	
7	AHU Fans input	(kWh)	30.1	30.1	
8	**Sub total**	**(kWh)**	**45.5**	**45.3**	**-0.4%**
9	Boiler input	(kWh)	38.0	0.0	
10	**Total consumption**	**(kWh)**	**83.5**	**45.3**	**-45.7%**
11	EvacTube output	(kWh)	162.8	187.2	
12	VPV/SA output	(kWh)	67.5	77.3	
13	**Total output**	**(kWh)**	**230.3**	**264.5**	**14.9%**
14	Storage tank heat loss	(kWh)	10.6	9.8	
15	HWS tank heat loss	(kWh)	10.8	10.0	
16	**Total storage heat loss**	**(kWh)**	**21.4**	**19.9**	**-7.2%**

OPTIMAL CONTROL STRATEGY

With a functioning, calibrated model of the building and its systems in place, the next stage of the work will be to develop an implement an optimal control strategy. During the unoccupied overnight period, an evolutionary optimization method will be used to devise a supervisory control trajectory for the next day. This will incorporate information relating to building use together with a short-term forecast for the following day's weather.

The control trajectory will then be updated during the day at 15 minute intervals, using an optimization algorithm (such as a micro-genetic algorithm) which is economical in function evaluations and has been shown to be capable of real-time application.

CONCLUSION

A system model has been developed and calibrated for a low-energy public building which incoporates solar air and water heating, a ventilated photovoltaic array, biomass boiler and active and passive thermal storage. The modular structure has enabled a supervisory control system to be integrated into the overall simulation.

The existing, prototype building has a building energy management system programmed according to standard engineering practice for a building of this type. Maximizing the performance of energy systems which incorporate both active and passive thermal storage is a difficult problem in itself: in this case the difficulty is compounded by the relative unfamiliarity of most designers to a range of renewable energy technologies, particularly as exhibited by the prototype building.

The combination of on-line modeling of the performance of the building and its systems, together with an optimization algorithm which is capable of devising optimal or near-optimal supervisory control trajectories would be particularly effective in an application where an historical legacy of engineering experience cannot be drawn upon.

This work has demonstrated that improvements to a 'best practice' control scheme can readily be achieved through the use of a detailed system model, underlining the potential for the production of optimal control schemes by combining the model with suitable optimization procedures.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of the Engineering and Physical Sciences Research Council (EPSRC) under grant GR/S30467, the collaboration of Trend Control Systems Ltd and the Oadby and Wigston District Council.

REFERENCES

Crabb, J. A., Murdoch, N. and Penman, J. M. 1987. A Simplified Thermal Response Model, Building Services Engineering Research and Technology, 8(1):13-19.

Hanby, V. I., Fletcher, D. W. F. and Jones, D. N. T. 2002. Optimal Supervisory Control Of Refrigeration Plant By Evolutionary Strategy, Proceedings of System Simulation in Buildings '02, Liege, Belgium, University of Liege.

Cartmell, B. 2004. The Energy Saving Potential of Multi-Operational Ventilated Photovoltaic Systems in the Built Environment, Ph.D. Thesis, De Montfort University, UK

Mathworks, 2005. Simulink® Documentation, http://www.mathworks.com/access/helpdesk/help/toolbox/simulink/

Mendes, N., Oliveira, G. H. C., de Araujo, H. X, 2001 Building Thermal Performance Analysis by Using Matlab/Simulink, Building Simulation 2001, Rio de Janeiro, Brazil, August 13-15, 2001

Gouda, M. M., Underwood, C. P., Danaher, S. 2003, Modelling the Robustness Properties of HVAC Plant under Feedback Control, Building Services Engineering Research and Technology, 24(4):271-280