Conference Presentation

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This is a paper presented at the 2017 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)

Recommended citation:

Jones, O., Sprake, D., Vagapov, Y. and Borzistaya, E. (2017), 'Modelling and development of energy management system in a domestic building: Case study'. In: Proc. 2017 IEEE NW Russia Young Researchers in Electrical and Electronic Engineering Conference, Moscow, Russia, 1-3 February 2017, pp. 429-434, DOI: 10.1109/EIConRus.2017.7910583

Modelling and Development of Energy Management System in a Domestic Building: Case Study

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***Abstract*—The paper discusses the modelling and development of an energy management system applied for a domestic building. The model has been created to determine energy requirements and takes into account the building fabric and associated energy losses. A number of scenarios were investigated using the model to demonstrate the energy and cost savings. The energy control system is developed to ensure that all separate components of the system interface with each other with the aim of reducing total energy use. The implementation of the systems for a particular domestic building is considered as a case study.**

Keywords—energy management, energy loss, domestic building, building model

I. Introduction

As energy prices continue to rise it is of great concern to the architects and builders that energy demand as a whole is not considered within the numerous building regulations. It is apparent that each source of energy consumption is treated individually and a top down or big picture approach to energy consumption and management with a domestic building is lacking in numerous new build projects. A lack of understanding of basic principles within the building community of low energy designs led to the realisation that a detailed study into energy consumption and how the systems are managed in relation to each other would provide significant cost savings in the long term for the house owners.

As part of Building Regulations a Standard Assessment Procedure (SAP) report is required to determine the energy rating of a new home. A SAP rating can range from 1 to 100+, 100 representing zero energy cost. The rating for existing houses can be improved on substantially by improving the original design with simple additions such as greater insulation and increased air tightness [1].

The paper discusses the implementation of house improvement in order to increase the SAP rating. The suggested improvements are based on results obtained from the modelling of a domestic building in the context of heat loss reduction. The improvement is also includes installation of energy management system to increase the energy and cost savings. A domestic building used as case study for modelling and analysis has the specification shown in Table I.

A number of scenarios were investigated using the model to demonstrate the energy and cost savings. Savings were considered over a 30 year period. All calculations were made using current energy prices, an assumption has been made that all energy costs will rise in the future relatively in line with each other. Any costings that were close to each other were recalculated adding 3% per year to each type of energy cost, this gave further clarity and understanding of potential future savings.

TABLE I HOUSE SPECIFICATION

House Areas and Volumes	Values
Windows areas	25 m^2
Door areas	4 m^2
Velux (roof windows) areas	6 m^2
Internal wall area	82 m^2
Internal roof area	189 m^2
Internal floor area	130 m^2
House total internal volume	338.25 m^3

II. Building Modelling

Heat loss within buildings occurs through three different mechanisms; convection, conduction and radiation. In a domestic environment this is typically seen as warm air rising from a radiator and as it reaches the ceiling cools down and drops down to where the air is cooler. This can lead to a feeling of drafts and cold spots as the air cools and falls [2].

The heat transfer in a building represents the heat passing through solid object such as walls, floors and roofs. As there is a temperature difference between the internal and external temperature the particles on the inner side will have a higher speed that they transfer to the slower moving, colder, outer ones. The heat transfer can be calculated by using the following formula:

$$H_t = uA\Delta t \tag{1}$$

where H_t is heat loss [W], u is heat transfer coefficient [W/m^{2}K], A is area [m^2], Δt is temperature difference [K].

$$\Delta t = t_{in} - t_{ex} \tag{2}$$

where t_{in} is the internal temperature; t_{ex} is external temperature.

To determine energy requirements a model was created that takes into account the building fabric, this includes levels

978-1-5090-4865-6/17/$31.00

of insulation in the walls, floors and roof. The energy loss through windows and doors were also incorporated into the model which also took into account solar gain throughout the year. It also gave an opportunity to model heat losses due to air changes (i.e. draughts) within the building. The model allowed numerous specifications to be considered and a total energy cost generated for each specification. The model also gave an indication of boiler sizing which ranged from 2 kW to 10 kW dependant on building fabric. The model was fully checked for accuracy and developed to take into account additional factors such as solar gain and seasonal effects.

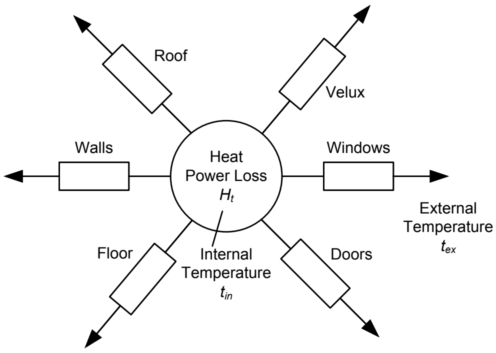

Fig. 1. Heat transfer model of the domestic building.

Comparing the results of the model to the existing SAP report showed an accuracy of 5% which gave confidence for its use for different specifications. It is worth noting at this point that the SAP report does not fully highlight the benefits of building a low energy consumption home, a good SAP rating can be achieved by using a solar photovoltaic array and low specification insulation. As with any assessment procedure it seems that industry have found the best way to achieve a pass for the minimum cost.

A. Insulation

As can be seen from Table II good insulation also needs to be considered also for an energy efficient design. Comparing different levels of achievable insulation values versus building regulation complaint values in an air tight structure with mechanical venting in place shows a saving of over £5000 over a 30 year period. For this project to reduce the heat transfer coefficient *u*, value for a timber framed wall using polyisocyanurate insulation from 0.3 to 0.10 W/m^{2}K would require increasing the insulation thickness from 60 mm to 180 mm [3]. This would be slightly more expensive and would not physically fit within the walls leading to a reduction in living space which is unacceptable. A compromise balancing cost, potential savings and available space was required. Further modelling led to the conclusion that a *u* value target for walls, floors and the roof should be a maximum of 0.15 W/m^{2}K but if space was available within the building that did not reduce the living areas the maximum amount of insulation should be used as it would provide a further reduction in energy demands.

B. Air Tightness and Ventilation

It was apparent from the calculations that a draughty building that had a leakage rate of 4 air changes per hour (this would pass the building regulations) would have energy losses of roughly twenty times that of a house that had a mechanical vent and heat recovery unit installed with air changes of 0.5 per hour [4]. See Table II for further costs when comparing an air tight building with mechanical vent and heat recovery installed to a non-airtight building with no mechanical ventilation. From the costing exercise it is clear that the initial outlay of £5000 for an airtight building fabric and vent system is well spent and would pay for itself in four years of running.

TABLE II MVHR COMPARISON

MVHR	Air Changes	kWh Year	Cost (£)
No MVHR	4	39134	1956.7
	3	27294	1364.7
MVHR Eff 90%	2	2459	122.95
	1	1936	96.8
	0.5	1674	83.7

The modelling in Table III shows a comparison of cost for using a Mechanical Vent and Heat Recovery (MVHR) system [5] against different levels of insulation. Modelling was also undertaken to compare different levels of insulation without a MVHR unit installed in a building that had two air changes per hour as shown in Table IV.

TABLE III INSTALLED MVHR WITH DIFFERENT LEVELS OF INSULATION

u (W/m^{2}K)	kWh Year	Cost 1Yr (£)	Cost 30Yr (£)
0.1	1215	60.75	1822.5
0.15	1983	99.15	2974.5
0.2	2751	137.55	4126.5
0.25	3655	182.75	5482.5
0.3	4626	231.30	6939.0

TABLE IV NO MVHR WITH DIFFERENT LEVELS OF INSULATION

u (W/m^{2}K)	kWh Year	Cost 1Yr (£)	Cost 30Yr (£)
0.1	15994	799.7	23991
0.15	17424	871.2	26136
0.2	19016	950.8	28524
0.25	20608	1030.4	30912
0.3	22201	1110.05	33301.5

As can be seen by the tables the biggest factor in saving energy is to ensure an airtight design. However, several other factors need to be taken into account when creating a relatively air tight design. Any design with a small number of air changes per hour needs to consider the build-up of gasses such as carbon dioxide and rising humidity within the living space. Mechanical ventilation is essential to ensure the internal air quality of the building and a comfortable living environment for the occupants [6]. The benefit of mechanical ventilation is that the number of air changes per hour can be controlled, the air quality can be maintained and the exhaust heat from the system can be recovered efficiently. Typical MVHR units have an energy efficiency of 90% or greater. In practice this means that 90% of the heat energy within the exhausted air is recovered and reintroduced to the building via the inlet air.

Another part of the building fabric that has a potential to minimise energy losses are windows and doors. Using windows with a *u* value of 2 W/m^2K (minimum building regulation 2010 value) would increase the predicted energy consumption by 2000 kWh per year compared to a triple glazed window with a u value of 0.8 W/m^2K [7]. Whilst this will lead to a saving of £3000 over a 30-year period. Upgrading to triple glazed windows will add approximately £5000 to the initial build cost. This measure seems counterproductive, however the installation of triple glazing will ensure that the temperature of the inner glass pane is high enough to keep variation of surface temperature within the property to less than 4°C. This will ensure that temperature stratification does not occur internally leading to draughts and a decrease in comfort levels. It is usual that if these cold spots exist the internal room temperature has to be increased to maintain comfort levels. Modelling a 2°C increase in internal temperature, to mitigate these cold internal areas, showed an increase in heating demand of 600 kWh per year, over a 30 year period this equates to a cost of roughly £1000. To summarise triple glazed windows will cost an additional £1000 over 30 years but will increase interior comfort and reduce energy demand by 2600 kWh per annum which the author deems to be a worth the additional outlay.

In addition to a good level of insulation the windows and doors will have to be as air tight as possible, they will require double seals and positive closure mechanism. Passivhaus approved windows usually have seals on the internal frame and an overlapping external frame that is also sealed to ensure air tightness. Windows are usually fitted with trickle vents to ensure air ventilation when they are closed, as a mechanical vent system is being fitted these vents aren't required.

C. Solar Gain

One concern of building an extremely well insulated house is overheating in the summer. In order to collect some reliable data two temperature loggers were installed, one externally in a shaded area and one within the master bed room of the property located in the roof. This was done between August and September 2015. Fig. 2 and Fig. 3 show the results. As the graphs demonstrate overheating is a strong possibility in periods of strong sunshine. The highest external temperature recorded was 20.1°C compared to the maximum external of 30°C. There are 19 times within the measurement timescale of 30 days that the interior temperature has increased above the desired 20°C, it is also worth considering at this point that the building was not fully insulated or air tight which was provided some cooling effects.

Finding reliable information on the amount of solar irradiation was difficult. Data was found for the model by using a solar PV output calculator that gave an indication of solar energy in kWh for an area taking into account it is orientation and angle towards the sun. To provide accurate results the angle of the 'solar panel' was entered as 90° to simulate a window and 30° (pitch) for a roof window. [7] This data when incorporated into the model showed that for 8 months of the year the house when taking solar gain into account would have an excess of energy and could lead to overheating. As can be seen in Table V May, June and July have over 6000 kWh of excess energy within the property. Any red figures shown in Table V show an excess of energy that needs to be prevented from entering the property.

To negate the effects of solar gain a number of options were researched. It is quite common in energy efficient builds for large overhangs to be incorporated above glazing to provide shade when the sun is high during summer months.

TABLE V MONTHLY HEATING DEMAND AND SOLAR GAIN FIGURES

2015	Monthly Heat Energy Input (kWh)	Solar Gain (kWh)	Difference (kWh)
January	1081	398	683
February	976	689	287
March	1030	1543	-513
April	898	2138	-1240
May	826	2769	-1943
June	652	2809	-2157
July	571	2624	-2053
August	571	2082	-1511
September	652	1518	-866
October	775	913	-138
November	898	463	435
December	1030	323	707

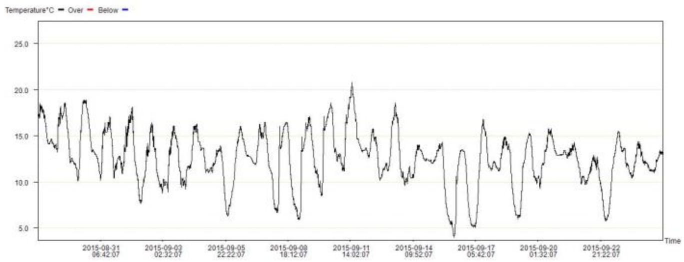

Fig. 2. External temperature: August – September 2015.

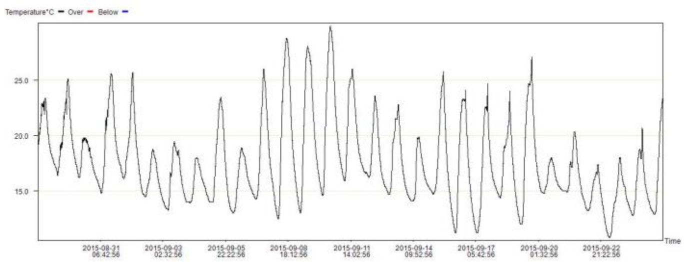

Fig. 3. Internal temperature: August – September 2015.

Internal blinds were also investigated however the solar energy would still enter the house through the glazing and be stored between the blinds and windows eventually leading to overheating. External blinds are available, these can be remotely controlled and incorporated into the proposed control system.

Air conditioning is also worthy of consideration; the assumption can be made that if internal temperatures are high due to solar gain there will be sufficient electricity generated from the solar panels to power a small air conditioning unit. This unit could be used for comfort cooling if the building was occupied during the day and closing the blinds was undesirable. There is a potential that this unit could also be used to provide some heat in the winter if a sudden temperature change was experienced, for example a door being left open for a long duration.

D. Heating

Using the model, the maximum heating loss in extreme low temperatures was estimated to be 2 kW. Compared to normal housing stock this is extremely low and difficult to achieve using conventional space heating methods. A number of options were considered such as pellet stoves, oil fired boilers, air source and ground source heat pumps and solar thermal. The common problem with these options was the fact that they could not modulate down efficiently to the lower power levels required. It will be quite typical in the house for a heating demand of only a few hundred watts to maintain the desired internal temperature. One option available for heating would be the installation of a number of water to air heat exchangers with the mechanical vent duct work. These are typically rated at 1 kW and would warn the air being transferred via the vent system. Another option would be a similar duct heater but containing an electrically powered heater in place of a heat exchanger. The preferred option would be to use a water to air heat exchanger that draws warm water from a thermal water store that is used for domestic hot water.

E. Domestic Hot Water

Whilst heating demand is very low in an energy efficient structure the hot water demand is totally dependent on the usage profile of the occupants. An Energy Saving Trust Report stated that typical usage for a 5 person property was 180 litres a day with a 95% confidence interval of ±18 litres. It is assumed that the worst case scenario will be 5 living in the house and the hot water calculations have been carried out on the basis of 180 litres per day. The incoming mains water at the property was measured throughout the tear and found to be 5°C at its lowest. This worst case figure was also used in the calculations. Desired hot water temperature for the property is 40°C. This gives a temperature difference of 35°C.

Therefore, $180 \text{ per day} \times 365 = 65{,}700$ litres of hot water per year. Water has a specific heat capacity of 4200 J/(kg·°C). Hence, the energy required can be found as $65{,}700 \times 4200 \times 35 = 9{,}657{,}900$ kJ or ~26 MWh per annum.

TABLE VI 30 YEAR LIFECYCLE COST OF VARIOUS HOT WATER OPTIONS

Option	Initial Cost	Cost per Year	Maintenance per Year	Total over 30 years
Oil Fired Boiler	£5000	£1750	£150	£62000
Electricity	£1000	£5250	£75	£160750
Solar PV + E7	£5000	£1050	£100	£39500
Biomass	£7000	£1400	£150	£53500
Air Source Heat Pump	£6500	£1750	£100	£62000

Several options were considered to deliver this significant heat demand such as pellet stoves, oil fired boilers, air source and ground source heat pumps, solar thermal, solar PV and Economy 7 (E7) tariffs.

The options were costed assuming a demand of 26 MWh and an additional 2 MWh for heating that would be drawn from a thermal store to take into account any losses. Consideration was also given to lifetime costs, this includes maintenance, replacement units and running costs per year over a 30 year period. Table VI shows the analysis.

As can be seen by the table the most cost effective option is to use solar PV to heat a thermal store during the day that is then topped up as required using E7 tariff. An E7 tariff provides 7 hours of electricity at non peak hours at roughly 1/3 of the peak hours unit cost. It was calculated that over a year a 4 kW solar PV could provide 40% of the required energy for hot water and the remaining 60% could be supplied by electricity during non peak times i.e. overnight. The thermal store would be fully 'charged' by the morning ready for the hot water demand. This option is most cost effective as 40% of the energy is provided for 'free' by the solar panels. Using the E7 tariff gives a per kWh cost of £0.05 which is currently very similar to oil. However, oil is a finite resource and it would be of benefit not to rely on it as supplies become less available.

III. CONTROL SYSTEM

There are numerous systems available on the market that promise lower energy bills by using 'smart' control systems. These usually allow some degree of control by the user via their mobile phone to change heating settings and switch the heating on as they approach home.

However, a control system is required that will monitor the internal temperature and take the most energy efficient action first if the temperature is outside the specified range. For example, closing the external blinds if the internal temperatures rise is the most energy efficient method available to stop overheating not switching on the air conditioning.

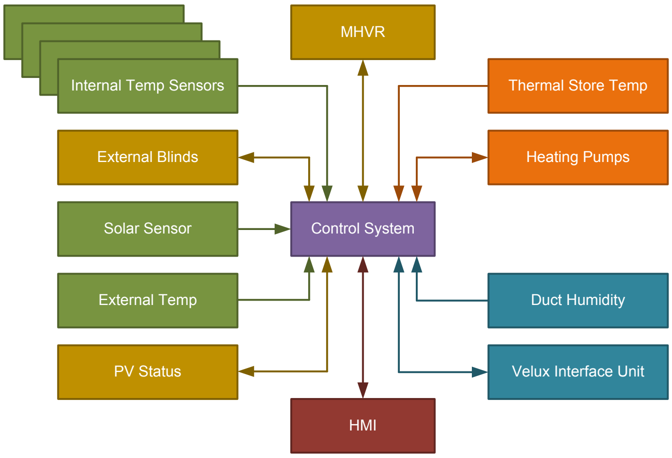

Fig. 4. System Block Diagram

The control system should provide control of numerous types of boilers, thermostats, windows, blinds etc. It would be of great benefit to designers of systems such as this one that all domestic appliances/plant equipment could communicate using the same protocol.

The proposed control system consists of a PLC with 18 inputs and 31 outputs, this is deemed sufficient for the project. Further expansion models can be purchased if future expansion is required. The unit is mounted in the ground floor plant room and all terminations for sensors are also made at this location. The unit has a small UPS to ensure control of the systems during power outages. A touch screen is provided and located in the main living area. This allows the user to change temperature etc. without having to enter the plantroom. The system block diagram is shown in Fig. 4.

The logic algorithm for the control has been design to provide operation of the system under maximum energy efficiency. There are numerous scenarios that have been assessed that are too many to list here. However, two examples have been discussed in this paper – (1) low temperature event and (2) high temperature event.

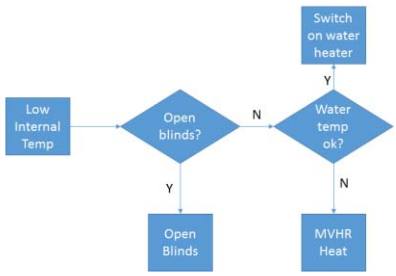

Fig. 5. Algorithm of the low temperature event.

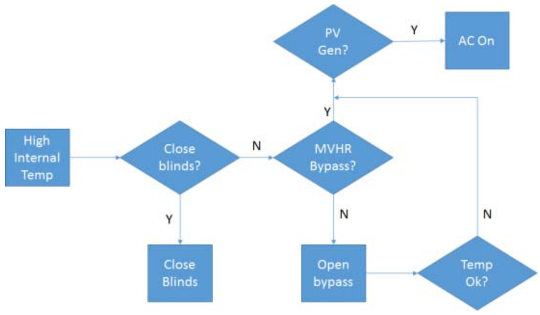

Fig. 6. Algorithm of the high temperature event.

As can be seen in Fig. 5 if a low temperature is detected the system should in the first instance determine if there is sufficient solar energy available to open the blinds to allow the internal areas to be warmed up using radiated energy from the sun. If this is possible the blinds should be opened and the system should monitor the temperature to see if it increases, if the temperature fails to rise the next step should be considered, if the thermal store is at an adequate temperature the pump should be started to circulate warm water to the water to air heat exchangers located in the vent system. If warm water is not available, the electric duct heater should be switched on. A further step that will be added to this logic is the operation of the air conditioning unit to provide heat if a significant boost in internal temperature is required.

A high temperature event shown in Fig. 6 initially follows the same logic as a low temperature event by checking if the blinds can be closed. If they can not be closed or are closed already the MVHR system will be checked to see if it can be changed to bypass mode, which is no heat recovery only cool external air introduced. If this is not possible or already in operation the system will check if the solar PV is generating, if it is the air condition unit will be switched on to rapidly cool the interior of the building.

IV. Conclusion

It has been shown by modelling that there are significant savings to be made by raising the specification of the building fabric at the initial design stage. All of the measures incorporated in the building fabric for the final design have a short payback period. An additional £15,000 spent at the build stage will have a payback period of 12-15 years. There is a potential for this payback period to decrease if energy prices for fossil fuels increase at a greater rate than other 'greener' focused options. The case study based on a proposed domestic building demonstrates that the energy savings can provide the results compared to SAP results within 5%. This gives a good indication of savings that could be achieved if the proposed system would be implemented.

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