

How to minimise space heating to dwellings in Wales, UK through the use of exhaust air source heat pumps: results of a post-occupancy monitoring study in Bargoed, UK



Dr John Littlewood
Director of EBERE
University of Wales
Institute Cardiff
UK
jlittlewood@uwic.ac.uk



Tim Taylor
KESS PhD Scholar
University of Wales
Institute Cardiff
UK
tjytaylor@uwic.ac.uk

Gareth Davies, United Welsh Housing Association, Caerphilly, UK, gdavies@uwha.co.uk.
David John, Insteng Ltd, Taffs Well, UK, davidjohn@insteng.co.uk.

Summary

This paper discusses a review of literature on the use of heat pumps for domestic space and water heating following a UK, German and Swiss study, as a context to a research project being undertaken in collaboration between the lead author from the Ecological Built Environment (EBERE) group at the University of Wales Institute Cardiff (UWIC) and United Welsh Housing Association (UW); a registered social landlord based in Caerphilly, UK. The research project is investigating the effectiveness of exhaust-air-source-heat-pumps for space and water heating in dwellings in Bargoed, UK. The methodology and results discussed and presented in this paper are from physical monitoring, which commenced in July 2010 on one dwelling, with a particular focus on the month of January 2011. It is demonstrated that by minimal intervention by the dwelling occupants, the energy use has been a nominal 176 kWh, which has resulted in a cost of just under £23.00 and led to carbon dioxide emissions of only 96 Kilograms. An expected output of the research will be the development of an educational guide for UW that discusses and illustrates the most effective method of post occupancy monitoring to inform future design and construction strategies and a protocol that will assist households to minimise energy costs and carbon emissions yet maintain comfort conditions, when living in dwellings that use heat pumps as their source of heating. The paper will be of interest to researchers, residential developers and landlords of dwellings.

Keywords: exhaust air source heat pumps, physical monitoring, carbon emissions, dwellings.

Introduction

This paper discusses some of the results of a physical monitoring programme being conducted at a residential development in Bargoed, UK, which commenced in September 2010 and finishes in August 2011. The first section of the paper discusses an overview of low carbon dwelling design and thermal performance and energy use monitoring protocols in the UK and current research which researchers from the EBERE group are undertaking in relation to monitoring dwellings. The second part of the paper presents the case study including discussion on the development ethos of UW, the methodological approach undertaken to undertake the monitoring study, including equipment used and some of the results which have been collected from January 2011.

Background

UK policy on low carbon dwelling design

The Climate Change Act 2008 commits the UK to legally-binding targets for greenhouse gas (GHG) emissions reductions of at least 34% by 2020 and 80% by 2050 against a 1990 baseline. The UK

housing stock accounts for approximately a quarter of total UK GHG emissions by end-use sector. Achieving deep GHG emissions reductions from the residential sector is therefore an “imperative” if these targets are to be met. New housing represents one of the easiest sectors of the economy to implement emissions reductions cost-effectively and in 2007 the UK Government announced its intention for all new homes to be built to a zero carbon standard from 2016. The performance targets of the zero carbon standard are to be implemented through progressive strengthening of the requirements of Approved Document L1A ‘Conservation of fuel and power in new dwellings’ (ADL1A) of Building Regulations.

Introduction to research programme

The first section of the paper has provided a brief overview of UK Government policy on low carbon dwelling design and on-going work by the EBERE research group to monitor and investigate the environmental performance of low carbon dwellings. This section introduces the aims and objectives of a research project that the lead author has been undertaking from the EBERE group at UWIC in collaboration with the Development department at UW. The aim of the research programme is to develop a monitoring protocol for UW which can be adopted on all recently completed dwellings and built into the design and construction process.

Case study

Introduction to United Welsh Housing Association

UW is a medium sized Housing Association providing affordable homes across South Wales, UK. Cemented within its corporate strategy is a commitment to invest in sustainable communities. UW have already built dwellings to meet levels four and five of the Code for Sustainable Homes and were the first UK registered social landlord to develop a level six (zero carbon) dwelling in 2010 at the Ebbw Vale regeneration park, which is also certified by the passivhaus institute.

Results

Data has been recorded since July 2010 to date (April 2011 at time of writing this paper). Between July and September 2010, was the commissioning period to test the equipment installed. The results presented in this paper were recorded in January 2011.

Discussion

The EST UK trial of heat pumps indicated that the performance in-use is often worse than the designed use [15]. From the results presented in Figs four to six above it could be argued that the installation of the EASHP in the case study dwellings at Park Crescent meets the designed performance and that there have been no problems with the installation, since the energy usage and associated CO₂ emissions and costs are minimal during one of the coldest winters in the UK, since 1986. The results presented are a snap-shot of the available data and future papers will indicate a more in-depth analysis of the monitoring in the case study dwelling.

In terms of the initial questions for the research study, the results thus far have indicated that the dwelling provides internal temperatures within comfort ranges, with minimal heating costs.

How to minimise space heating to dwellings in Wales, UK through the use of exhaust air source heat pumps: results of a post-occupancy monitoring study in Bargoed, UK



Dr John Littlewood
Director of EBERE
University of Wales
Institute Cardiff
UK
jlittlewood@uwic.ac.uk



Tim Taylor
KESS PhD Scholar
University of Wales
Institute Cardiff
UK
tjytaylor@uwic.ac.uk

Gareth Davies, United Welsh Housing Association, Caerphilly, UK, gdavies@uwha.co.uk.
David John, Insteng Ltd, Taffs Well, UK, davidjohn@insteng.co.uk.

Summary

This paper discusses a review of literature on the use of heat pumps for domestic space and water heating following a UK, German and Swiss study, as a context to a research project being undertaken in collaboration between the lead author from the Ecological Built Environment (EBERE) group at the University of Wales Institute Cardiff (UWIC) and United Welsh Housing Association (UW); a registered social landlord based in Caerphilly, UK. The research project is investigating the effectiveness of exhaust-air-source-heat-pumps for space and water heating in dwellings in Bargoed, UK. The methodology and results discussed and presented in this paper are from physical monitoring, which commenced in July 2010 on one dwelling, with a particular focus on the month of January 2011. It is demonstrated that by minimal intervention by the dwelling occupants, the energy use has been a nominal 176 kWh, which has resulted in a cost of just under £23.00 and led to carbon dioxide emissions of only 96 Kilograms. An expected output of the research will be the development of an educational guide for UW that discusses and illustrates the most effective method of post occupancy monitoring to inform future design and construction strategies and a protocol that will assist households to minimise energy costs and carbon emissions yet maintain comfort conditions, when living in dwellings that use heat pumps as their source of heating. The paper will be of interest to researchers, residential developers and landlords of dwellings.

Keywords: exhaust air source heat pumps, physical monitoring, carbon emissions, dwellings.

1. Introduction

This paper discusses some of the results of a physical monitoring programme being conducted at a residential development in Bargoed, UK, which commenced in September 2010 and finishes in August 2011. The results focus on the winter month of January 2011, which was one of the coldest winters on record for many years in the UK. The first section of the paper discusses an overview of low carbon dwelling design and thermal performance and energy use monitoring protocols in the UK and current research which researchers from the EBERE group are undertaking in relation to monitoring dwellings. In addition, a review of a published UK wide study on the use of heat pumps in dwellings to provide heating is also discussed, in comparison to a study from Germany and Switzerland. The second part of the paper presents the case study including discussion on the development ethos of UW, the methodological approach undertaken to undertake the monitoring study, including equipment used and some of the results which have been collected from January 2011.

2. Background

2.1 UK policy on low carbon dwelling design

The Climate Change Act 2008 commits the UK to legally-binding targets for greenhouse gas (GHG) emissions reductions of at least 34% by 2020 and 80% by 2050 against a 1990 baseline [1]. The UK housing stock accounts for approximately a quarter of total UK GHG emissions by end-use sector [2]. Achieving deep GHG emissions reductions from the residential sector is therefore an “imperative” if these targets are to be met [3]. New housing represents one of the easiest sectors of the economy to implement emissions reductions cost-effectively [4] and in 2007 the UK Government announced its intention for all new homes to be built to a zero carbon standard from 2016 [5]. The performance targets of the zero carbon standard are to be implemented through progressive strengthening of the requirements of Approved Document L1A ‘Conservation of fuel and power in new dwellings’ (ADL1A) of Building Regulations [6].

Lowe & Oreszczyn [7] argue that it will be essential to monitor and evaluate the energy and carbon performance of new dwellings in the UK to appraise the impact and success of policy implementation for zero carbon homes. Further drivers for monitoring the performance of new dwellings are identified by Taylor et al. [8]:

- Supporting product and process innovation for new design and construction methods and technologies;
- Developing knowledge and expertise in the development of low carbon dwellings through providing feedback to the clients and design and construction teams; and
- Informing the development of design standards and regulatory instruments and thus connecting policy aims with practice.

2.2 Current EBERE research on monitoring the environmental performance of dwellings

The first author of the paper is leading a number of projects to investigate via monitoring the performance of low carbon buildings and low carbon technologies for new dwellings and retrofitting to deprived existing dwellings in Wales, UK. This includes UWIC’s contribution to work package six of the Low Carbon Built Environment project; a 39 month project that commenced in July 2010. The second author commenced a three-year doctoral research project (the director of studies for this project is the first author of this paper) at UWIC in February 2010, which is investigating the environmental performance of four case study apartment buildings in Swansea to determine if, in practice, low-carbon design is translated into low-carbon construction and performance in-use [8], 9]. Both projects aim to address the general lack of detailed empirical evidence of the performance of low carbon dwellings in the UK [7]. Furthermore, these projects also aim to test and develop protocols and publish guidance for the monitoring and evaluation of building environmental performance for Registered Social Landlord (RSL) housing developers. This builds upon recent research work in the UK for developing monitoring protocols for low carbon dwellings [11].

In addition, to the carbon performance targets introduced in the preceding section of the paper, residential developers in the UK are subject to other planning and development requirements. For example, since September 2010 all new dwellings in Wales have been required to meet Level three of the Code for Sustainable Homes (CfSH) as a condition of receiving planning permission [13] & 14]. This paper reports on the results of a residential case study where each of the dwellings have utilised exhaust-air-source-heat-pump (EASHP) to deliver these environmental objectives.

2.3 Introduction to air source heat pumps

In domestic heating applications, a heat pump operates by moving heat from a low temperature “heat source” (e.g. ambient air) and delivering it to a higher temperature “heat sink” to provide central heating or domestic hot water (DHW) [15]. For an exhaust air source heat pump, the heat source is the air inside the house extracted by a controlled (mechanical) ventilation system. The heat sink can be either under-floor heating or radiators for space heating, or a DHW boiler system

(or a combination of space heating and DHW systems). The heat pump uses electricity to “pump” heat from the lower temperature source to the higher temperature sink, and a well-installed air source heat pump with good performance can deliver 3kW of heat for every 1kW electricity used [16] (the ratio of heat supplied to the electrical energy used by the heat pump is known as the coefficient of performance, or COP).

A recent study by the Energy Saving Trust (EST) [15] investigated the performance of heat pumps installed in new and refurbished homes in the UK. Following a one-year field trial, it was found that the performance of both air source and ground source heat pumps varied widely. In summary, the study found that [15]:

- The performance of heat pump systems is sensitive to system design, installation and commissioning practices and user behaviour;
- Control systems were generally too complicated for users to understand how to operate the heat pump efficiently and effectively;
- Many systems appeared to be incorrectly installed; and
- The installation of heat pumps often involved many trades (e.g. plumber, electrician) and in some cases this blurred responsibilities for the eventual performance of the whole system;

A subsequent research study compared the results of the EST trial with similar trials of heat pumps in Germany and Switzerland [17]. Although some air source heat pumps in the UK trial achieved similar levels of performance as the German and Swiss installations, many did not perform as well. The study concluded that the observed gap between the performance of the heat pumps in the UK trial and those in Switzerland and Germany could be closed through concerted efforts to improve the knowledge and skills of installers [17].

3. Introduction to research programme

The first section of the paper has provided a brief overview of UK Government policy on low carbon dwelling design and on-going work by the EBERE research group to monitor and investigate the environmental performance of low carbon dwellings. This section introduces the aims and objectives of a research project that the lead author has been undertaking from the EBERE group at UWIC in collaboration with the Development department at UW. The aim of the research programme is to develop a monitoring protocol for UW which can be adopted on all recently completed dwellings and built into the design and construction process.

For the case study presented in this paper, the aim above has been further refined to investigate the environmental performance, occupancy behaviour and occupant attitudes towards the Park Crescent dwellings and the questions include:

1. Has the low carbon design approach i.e. increased insulation, renewables: DSHW panels and exhaust air source heat pump (EASHP) led to lower carbon emissions?
2. Are the heating systems in the dwellings easy to operate?
3. Are the dwellings comfortable i.e. do they provide a stable internal temperature throughout the annual climatic year?
4. Do the dwellings have reduced utility costs for space and water heating and power?
5. What can be learnt from this project for future dwellings?
6. Does the dwelling design and construction approach, heating and renewable energy systems need to change?

4. Case study

4.1 Introduction to United Welsh Housing Association

UW is a medium sized Housing Association providing affordable homes across South Wales, UK. Cemented within its corporate strategy is a commitment to invest in sustainable communities. UW have already built dwellings to meet levels four and five of the Code for Sustainable Homes and were the first UK registered social landlord to develop a level six (zero carbon) dwelling in 2010 at

the Ebbw Vale regeneration park, which is also certified by the passivhaus institute [18]. This initial design for this dwelling was procured through a design competition in 2009. The lead author of this paper contributed to the design of the scoring system and acted on UW's behalf to contribute to the judging of the 43 dwellings submitted for review in the competition. The UW emphasis on sustainability is due to the aspiration that all their tenants are able to live greener lives; whilst minimising fuel poverty and carbon emissions. UW has been working with the lead author of this paper at UWIC since June 2009 and in September 2009 they jointly won a European Social Fund grant to sponsor a doctorate student to investigate and develop the UW model for ecological communities, see [19].

4.2 The case study site

The case study development consists of 24 houses (22 with three bedrooms and two with four bedrooms on two storeys) and two apartments (two bedroom on one storey) as illustrated on the site plan in Fig 1 below. The development is known as Park Crescent and is situated in Bargoed, Wales, UK. Park Crescent was completed in spring 2009 and therefore the majority of occupants have been resident for two years. Park Crescent is on a latitude and longitude of 51.7 and 3.2 degrees, respectively and an altitude of 220 mts. Each dwelling has been designed to code level three of the code for sustainable homes and level four for the energy category [14]. The heating strategy for each dwelling designed to trial the use of NIBE 360p EASHPs supplying underfloor heating [20]. The NIBE 360p works on two cycles, air-to-water for space heating, which involves extracting air from two internal rooms (kitchen and bathroom) and water-to-water for domestic hot water, from a roof mounted four meter squared solar panel [ibid]. Unusually for UK sub-urban development the development site does not have a supply of natural gas as a fuel, a deliberate choice of UW. The case study dwelling is highlighted at the top left of Fig 1 and is a three bedroom house, which is occupied by two adults (between April; 2009 and December 2010 and one adult from January 2011) and two children.

Fig. 1 Site plan for Park Crescent, Bargoed, UK & the case study dwelling



4.3 Research methods

Sections 4.3.1 to 4.3.4 discuss and illustrate the monitoring methodologies which have been adopted at Park Crescent, which commenced in June 2010.

4.3.1 Sensors to monitor climatic data

In June 2010, a Davis Vantage Pro2 weather station was installed above the roof ridge line on the case study dwelling, which records a number of variables, as illustrated in Fig 2 and Table 1 below

[21].

Fig. 2 Davis Vantage Pro2 weather station installed on the case study dwelling



Table 1: Davis weather station, Vantage Pro2

Variables recorded	Units of measurement	Recording interval
Air Temperature	Fahrenheit	10min
Humidity	Percentage	10min
Wind Speed	MPH	10min
Wind Direction	NSEW	10min
Heat Index	Fahrenheit	10min
Barometric Pressure	mBar	10min
Rain	inches	10min
Solar	W/m ²	10min

The Davies Vantage Pro2 Weather Station is connected via ethernet to a broadband router in the case study dwelling, which then sends data back to a Davis hosted site, which can be assessed via the Internet and live data is summarised here: <http://www.weatherlink.com/user/uwhapkcs48/index.php?view=main&headers=1>.

4.3.2 Sensors to monitor internal energy use

Five circuits are being recorded for their electricity usage, as indicated in Table 2 below. The number of circuits which could be monitored was limited by the connections of the DT80 datalogger.

Table 2: Circuits recorded

Manufacturer	Variables recorded	Units of measurement	of Accuracy	Recording interval
INSTeng	Electricity usage of	kWh	± 0.5% FSD	10min
	EASHP			10min
	Total Power			10min
	Sockets			10min
	Lights			10min
	Cooker			10min

4.3.3 Sensors to monitor internal conditions

Nine internal rooms (ground floor hall, lounge, kitchen/diner and bathroom; first floor landing, three bedrooms and bathroom) are monitored in the case study dwelling and the sensors in each room record the air temperature, relative humidity and the position of each openable window (open or closed), as indicated in Table three illustrated on Fig three below.

Table 3: Internal conditions recorded

Manufacturer	Variables recorded	Units of measurement	of Accuracy	Recording interval
INSTeng	Air temperature	Centigrade	0.5°C	10min
	Humidity	%	± 2%	10min
	Window switch	Open/closed	n/a	10min

Fig. 3 Insteng sensor for recording internal air temperature, relative humidity & fenestration position



4.2.4 Datalogging

Data is collected from the internal conditions and the electrical circuits are all sent by internal wireless network to the “DT80” [22]. The temperature, humidity & Window contact are transmitted via wireless to a base station, which then communicates to the Datalogger via RS232 Modbus RTU protocol. All data from the base station is then logged. The energy kWh pulse are monitored by current transducers mounted in the distribution board, the kWh pulse is then wired directly to the DT80 inputs & logged by the Datalogger. Other conditions such as EASHP & Solar Temperatures / Flow, CO₂% are directly wired to the DT80 and logged by the Datalogger. The Datalogger is connected via ethernet to a broadband router enabling data to be transmitted to an FTP site (Hosted by INSTeng Process Automation.) The data logged every 10min is downloaded to the FTP site daily (at midnight) in the form of a CSV file.

4.4 Results

Data has been recorded since July 2010 to date (April 2011 at time of writing this paper). Between July and September 2010, was the commissioning period to test the equipment installed. The results presented in this paper were recorded in January 2011.

4.4.1 Results period January 2011

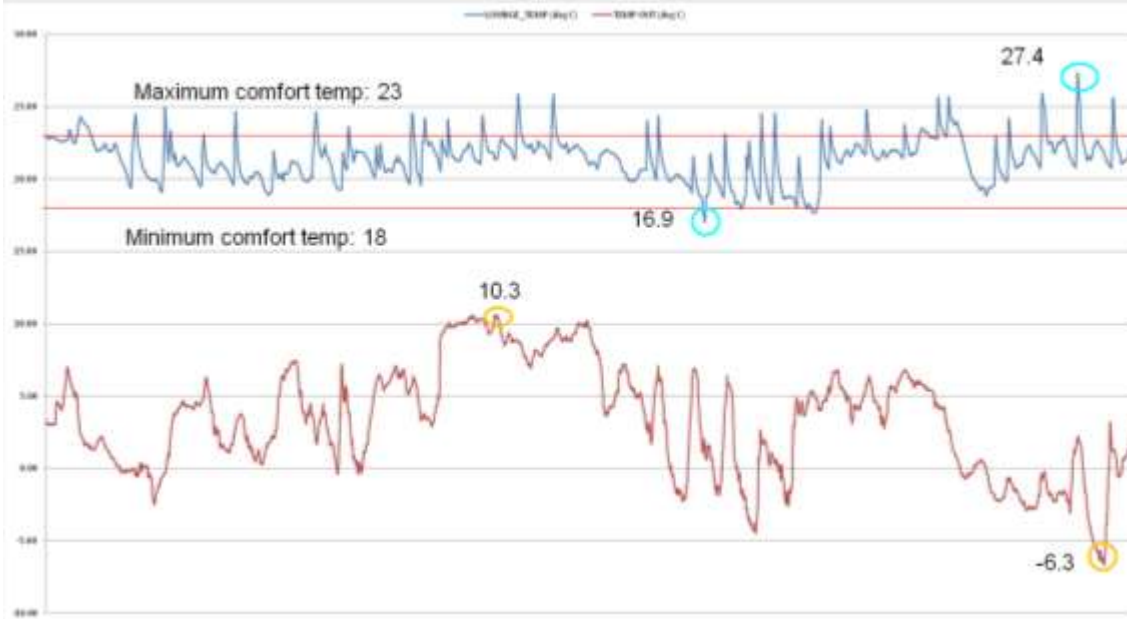
In the UK, 2010 was on average the coldest year since 1986 and the winter period was the coldest since at least 1970 [2]. Milder temperatures were recorded in January, although these were still below the 1971 to 2000 average [23]. Overall, between 2009 and 2010 there was a corresponding 13% rise in CO₂ emissions from the residential sector in the UK, reflecting an increased use of

domestic gas for space heating [2]. Mean temperatures for January 2011 as a whole were somewhat below the 1971 to 2000 average, especially over Northern Ireland and other western areas [ibid].

4.4.2 Recorded Results

Figures four to six below illustrate the internal conditions in the ground floor lounge and first floor bedroom (occupied by one adult) versus the external climatic conditions and also the power consumption of the EASHP.

Fig. 4 Ground floor lounge air temperature versus external air temperature, January 2011



The winter design temperature range for living rooms in the UK as recommended by the Chartered Institute of Building Services Engineers (CIBSE) is 22 to 23 degrees centigrade ($^{\circ}\text{C}$) [24] and by Borer [25] is 18 to 23 $^{\circ}\text{C}$. It can be seen from Fig four above that on several occasions (31 in total, linked to each day of the month) during January 2011 the interior air temperature in the lounge exceeds 23 $^{\circ}\text{C}$ and the highest temperature is 27.4 $^{\circ}\text{C}$. This is 4.4 degrees Kelvin above the upper comfort range for a lounge in UK dwellings [24]. On all only two days does the internal air temperature dip below the minimum comfort temperature of 18 $^{\circ}\text{C}$. By contrast the exterior air temperature has a maximum and minimum of 10.3 and -6.3 $^{\circ}\text{C}$, a 16 $^{\circ}\text{C}$ temperature range.

The winter design temperature range for bedrooms in the UK as recommended by CIBSE is 17 to 19 $^{\circ}\text{C}$ and by Borer [25] 18 to 20 $^{\circ}\text{C}$. It can be seen from Fig five below that on several occasions (15 in total) during January 2011 the interior air temperature in the lounge exceeds 20 $^{\circ}\text{C}$ and the highest temperature is 21.2 $^{\circ}\text{C}$. This is 3.2 K above the upper comfort range for a bedroom in UK dwellings [25]. The internal air temperature dips below the minimum comfort temperature of 18 $^{\circ}\text{C}$ on 15 days during January and the coldest temperature is 16.8 $^{\circ}\text{C}$, 1.2 K below the minimum comfort range of 18 $^{\circ}\text{C}$ [25].

Fig. 5 First floor bedroom air temperature versus external air temperature, January 2011

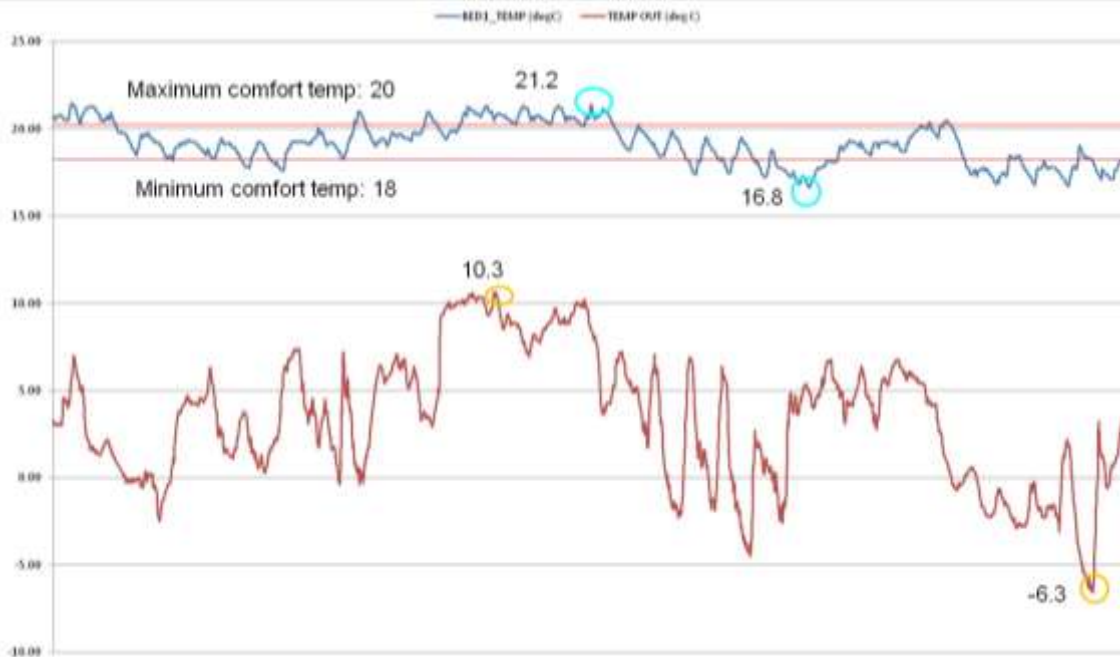
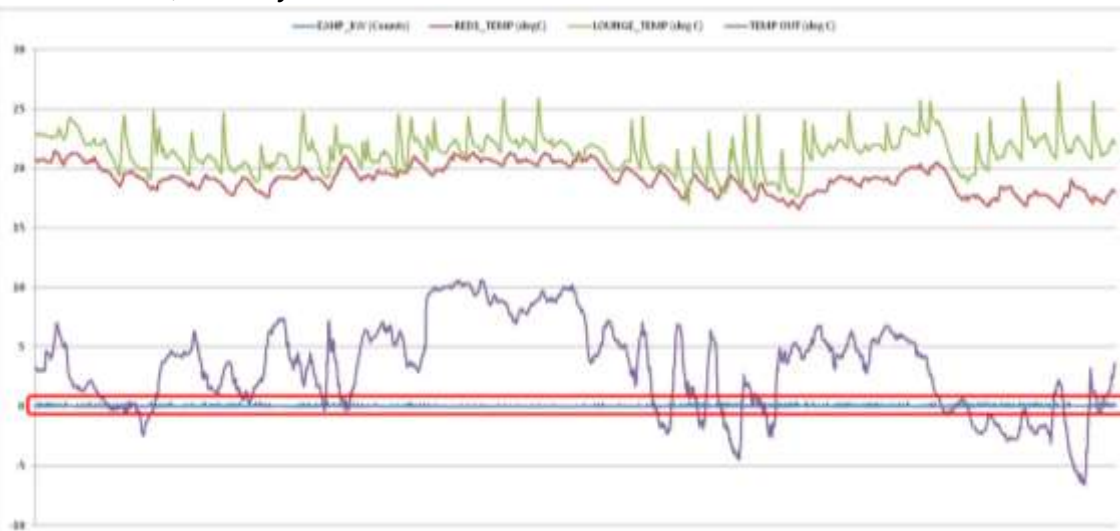


Fig. 6 Lounge and bedroom air temperature versus external air temperature & power consumption of the EASHP, January 2011



When analysing the data for the power consumption of the EASHP for January 2011, it was anticipated that the associated energy costs and CO₂ emissions would be excessively high, based on the cold exterior air temperature in January 2011 and the very warm internal air temperatures during the same month, which often exceeded the upper comfort range of 23°C and 20°C for the lounge and bedroom. The power consumption of the EASHP is illustrated in Fig six running from left to right just above the '0' unit on the y axis and indicated by the red band; it is almost negligible. The total power consumption for space and water heating by the EASHP for January 2011 was only 175.58 kWh, which equates to £22.85 at a unit cost £0.13 per kWh and 95.73 Kg CO₂e per unit. An EASHP if designed and installed correctly, which appears to be the case from the results presented in this paper, perform particularly well as heat recovery devices. This is because the evaporator and condenser temperatures are closer together than when outside air is the source, as in air source heat pumps. With an EASHP, the temperature lift for the supplied air is less than a conventional air source heat pump, the pumping is easier and as a result the power consumption and associated carbon emissions are less also.

5. Discussion

The EST UK trial of heat pumps indicated that the performance in-use is often worse than the designed use [15]. From the results presented in Figs four to six above it could be argued that the installation of the EASHP in the case study dwellings at Park Crescent meets the designed performance and that there have been no problems with the installation, since the energy usage and associated CO₂ emissions and costs are minimal during one of the coldest winters in the UK, since 1986. The results presented are a snap-shot of the available data and future papers will indicate a more in-depth analysis of the monitoring in the case study dwelling.

In terms of the initial questions for the research study, the results thus far have indicated that the dwelling provides internal temperatures within comfort ranges, with minimal heating costs.

6. Conclusions

The paper has discussed an overview of low carbon dwelling design and thermal performance and energy use monitoring protocols in the UK and current research which researchers from the EBERE group at UWIC are undertaking in relation to monitoring dwellings in the UK. In addition, a review of a published UK wide study on the use of heat pumps in dwellings to provide heating was also discussed, in comparison to a study from Germany and Switzerland. The second part of the paper has discussed and illustrated the methodology adopted since June 2010 for a physical monitoring programme of a case study dwelling in Bargoed, UK. The results have demonstrated that for one of the coldest winter's on record in the UK since 1986, the internal temperatures during January 2011 are well within comfort ranges for UK dwellings (in the lounge and bedroom) and often exceed the top of the comfort range, yet energy costs and associated CO₂ emissions from the use of an EASHP are minimal at just over £22.00 (space and water heating) and 95.73 Kg CO₂e per unit.

7. Acknowledgements

The project is funded by and United Welsh Housing Association and University of Wales Institute Cardiff. Thanks are given to the tenants of United Welsh Housing Association at the case study site for their patience and co-operation with the research programme.

8. References

- [1] OPSI. "Climate Change Act 2008 (c. 27)". London, UK: HMSO; 2008.
- [2] NATIONAL STATISTICS. "Statistical Release - UK Climate Change Sustainable Development Indicator: 2010 greenhouse gas emissions, provisional figures and 2009 greenhouse gas emissions, final figures by fuel type and end user" [internet]. DECC, 2011. Available: http://www.decc.gov.uk/assets/decc/Statistics/climate_change/1515-statrelease-ghg-emissions-31032011.pdf [Accessed 11 April 2011].
- [3] BOARDMAN, B "Home Truths: A Low-Carbon Strategy to Reduce UK Housing Emissions by 80% by 2050". Oxford, UK: Environmental Change Institute, 2007.
- [4] LEVINE, M., D. ÜRGE-VORSATZ, K. BLOK, L. GENG, D. HARVEY, S. LANG, G. LEVERMORE, A. MONGAMELI MEHLWANA, S. MIRASGEDIS, A. NOVIKOVA, J. RILLING, H. YOSHINO. Residential and commercial buildings. In: "Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change" [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.
- [5] CLG. "Building a Greener Future: policy statement". London, UK: CLG; 2007.
- [6] CLG. "Building Regulations 2000: Approved Document L1A Conservation of fuel and power in new dwellings October 2010 edition". London, UK: NBS; 2010.
- [7] LOWE R, ORESZCZYN T. "Regulatory standards and barriers to improved performance for housing". *Energy Policy*. 2008, Vol. 36, pp.4475-4481.
- [8] TAYLOR T, LITTLEWOOD J, GEENS A, COUNSELL J, PETTIFOR G. "Development of a strategy for monitoring the environmental performance of apartment buildings in Swansea:

- measuring progress towards zero carbon homes in Wales” [Internet]. In: *Proceedings of RICS COBRA 2010 conference*, Paris France: 2-3 September 2010. [cited 2011 Feb 6] Available from: <http://www.rics.org/cobra>
- [9] TAYLOR T, LITTLEWOOD J, GEENS A, COUNSELL J, PETTIFOR G. “Developing post-occupancy evaluation techniques for assessing the environmental performance of apartment buildings in Wales: An ecological perspective”. In: *Proceedings of 9th International Detail Design in Architecture conference*, Preston UK: 4-5 November 2010.
- [10] TAYLOR T, LITTLEWOOD J, GOODHEW S, GEENS A, COUNSELL J, HOPPER J, SHARP D, “In-construction testing of the thermal performance of dwellings using thermography” (forthcoming) *International Conference on Sustainability and Energy in Buildings*, Marseille France: 1-3 June 2011.
- [11] EST. “CE298: Monitoring energy and carbon performance in new homes” [Internet]. London, UK: 2008. [cited 2011 Mar 28] Available from: <http://www.energysavingtrust.org.uk/business/Global-Data/Publications/Monitoring-energy-and-carbon-performance-in-new-homes-CE298>
- [12] HOMES & COMMUNITIES AGENCY. “Monitoring Guide for Carbon Emissions, Energy and Water Use - The Carbon Challenge: developing an environmental evaluation of housing performance in new communities” [Internet]. Homes & Communities Agency; 2010. [cited 2010 Dec 28] Available from: http://www.homesandcommunities.co.uk/public/documents/HCA_Carbon_Challenge_1.pdf
- [13] WELSH ASSEMBLY GOVERNMENT. “Planning for Sustainability” [Internet]. In: Planning Policy Wales. 2011. [cited 2011 Mar 28] Available from: <http://wales.gov.uk/docs/desh/publications/110228ppwchapter4en.pdf>
- [14] CLG. “Code for Sustainable Homes Technical guide (Version 2, May 2009)” [Internet]. London: CLG; 2009. [cited 2010 Oct 8] Available from: http://www.planningportal.gov.uk/england/professionals/buildingregs/sustainablehomes/bcco_detechnicalguide
- [15] EST. “Getting warmer: a field trial of heat pumps”. London, UK: Energy Saving Trust, 2010.
- [16] EST. “Air source heat pumps” [Internet]. Available from: <http://www.energysavingtrust.org.uk/Generate-your-own-energy/Air-source-heat-pumps> [Accessed 12 April 2011]
- [17] DELTA ENERGY & ENVIRONMENT. “Heat Pumps in the UK: How Hot Can They Get?” [Internet]. Available from: http://www.sepemo.eu/fileadmin/red/Publications/Delta_Heat_Pump_Trials_Whitepaper_January_2011.pdf [Accessed 12 April 2011]
- [18] UNITED WELSH HOUSING ASSOCIATION. 2011. “The UK’s first zero-carbon passive house”. Cited at: <http://www.uwha.co.uk/About/news/Welsh%20Passivhaus.htm>; available and accessed 13th April 2011.
- [19] HOLMES, D. COUNSELL. J, A, M. LITTLEWOOD, J. R. GEENS, A. J. DAVIES, G. “An exploration of low carbon and ecological dwellings, for the social housing sector in Wales, UK”. Paper submitted to the SB11 international conference
- [20] NIBE. “NIBE Exhaust Air Heat Pumps Help Meet New Eco-Targets”. Cited at: <http://www.nibe.co.uk/Home-Owner/NIBE-Heat-Pump-News/Bramall-Construction-Achieve-Code-Level-4-With-NIBE-Heat-Pump/> accessed 15th April 2011 (available).
- [21] DAVIS. “Vantage Pro2”. Cited at: <http://www.davisnet.com/weather/products/vantage-professional-weather-stations.asp>; available and accessed 15th April 2011.
- [22] DATATAKER. “Datataker dataloggers”. Cited at: <http://www.datataker.com/products/dt80.html>; available and accessed 15th April 2011.
- [23] BBC WEATHER. “UK Review – January 2011” [Internet]. Available from: http://news.bbc.co.uk/weather/hi/uk_reviews/newsid_9386000/9386839.stm [Accessed 12 April 2011]
- [24] CIBSE. 2007. “CIBSE Guide, Volume A, Design Data”. The Chartered Institute of Building Services Engineers, London, UK.
- [25] BORER P. HARRIS C. 1998. “The Whole House Book – Ecological building design and materials”. Centre For Alternative Technology, Machynlleth, Wales, UK.