Holistic Dwelling Energy Assessment Protocol for Mine-water District Heat Network

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Abstract. UK buildings and energy infrastructures are heavily dependent on natural gas and a large proportion is used for domestic space heating; but 50% is imported. Improving energy security and reducing carbon emissions are major government drivers for reducing gas dependency. So, there needs to be a wholesale shift in the energy provision to householders without impacting on thermal comfort levels, convenience or cost of supply. Electrical powered heat pumps are seen as a potential alternative system for heating new dwellings, but will they work in dwellings built prior to 1919? This paper investigates the energy demand of pre-1919 dwellings in Wales, UK as part of a feasibility study to extract water from disused coal-mines to supply a district heat network. A holistic surveying protocol providing a more accurate/realistic assessment of total household heat demand are considered. The protocol's techniques, include condition surveys, air permeability and thermography tests, and heat loss calculations are discussed. The results were used to predict future (beyond 2019) heat demand after potential retrofit improvements, thereby informing the size of heat pumps required. The findings show estimated heat demand to be in close correlation to household energy bills, and that the use of heat pumps in pre-1919 dwellings is viable, provided sufficient improvement to thermal performance is possible.

Keywords: Heat demand, Heat pump, Renewable energy, Retrofit, Pre-1919 Dwellings, Wales, UK.

1 Introduction

The thermal performance of the majority of the existing housing stock in Wales bears testimony to the quality of construction from pre-1919, and falls far below the minimum currently set by UK building standards in 2019 [1, 2]. Since 2010, significant sums of money have been invested to improve energy efficiency and combat fuel poverty in some of the most deprived areas of Wales, by retrofitting thousands of dwellings through the Arbed1, 2 and 3 schemes with exterior wall insulation, roof insulation, new boilers and controls, windows [3, 4]. Increasing energy efficiency of older properties remains a significant challenge, which cannot be achieved through insulation and air-tightness interventions alone, particularly when alterations to historically important architectural features of the building are not permitted [5]. So, alternative solutions are needed, which is explored in this paper. Namely, the feasibility of using water from the extensive network of former colliery workings as the basis for a district heating network [6]. The paper discusses the context to the need to decarbonise the energy supply for dwellings in Wales; the methodology used in a holistic protocol piloted on eight dwellings in a case study village of 7000 properties as part of the Caerau Heat Network project; the findings and recommendations from the feasibility study [7].

2 Context to energy demand in the UK in 2019

Heat accounts for nearly half of the energy consumed in the UK and about a third of carbon emissions [8]. Peak gas demand in typical winters exceeds electricity use by around five times, so it will not be possible to deliver UK carbon reduction targets while gas remains the primary source of energy for heating. Substitution of gas heating with direct electrical heating is currently not an option, as there is insufficient capacity in the electrical generation and distribution grid to meet the demand [9]. In spite of the efforts to improve dwellings in the Arbed 1 to 3 programmes (with circa £110 Million grant funding) estimates by the Welsh Government in 2018 suggest that 23% of households in Wales spend more than 10% of income on energy bills and are thereby considered to be in fuel poverty [4, 10]. Many socioeconomic factors contribute to these percentages, however the problem is exacerbated by the age and consequent poor energy performance of much of the housing stock in Wales and indeed the UK as a whole. Caerau, in the Bridgend County Borough Council (BCBC) region of south-west Wales was a once proud and prosperous coal mining village, but in 2015 was rated as the fifth most deprived community in Wales [11]. The majority of properties in the village were built in the early 1900s to meet the growing demand for labour in the local colliery, which operated from 1889 – 1979 and at its peak employed 2400 workers.

In 2017, BCBC sought a solution for heating the current community of approximately 7000 inhabitants, while simultaneously addressing the energy trilemma of decarbonisation, increasing security of supply and reducing the cost of energy [6]. There were no sources of waste heat to be exploited in the area, however the practicality of using water from the extensive network of former colliery workings as the basis for a district heating network was deemed worthy of further investigation. Measurements from an exploratory bore hole found the temperature of the mine water to be over 20 degrees Celsius (^{0}C) at 220 metre (m) depth [12]. Large volume pumping tests have yet to be completed, therefore the volume of water available and expected temperature drop for a network supplying between 150 and 850 households is currently unknown. However initial indications are that mine water could provide a better temperature source that the 11^{0}C than would be expected from a standard ground source heat pump and bore hole [13]. The feasibility of using either a centralised or decentralised heat pump network to provide heat to properties in Caerau was explored. In the centralised model, one or more large heat pumps would be used to heat water at the point where it was extracted from the mine workings, the hot water would then be circulated around the village in insulated pipes buried underground. Heat exchangers in houses connected to the network would transfer the thermal energy from the heated mine water to a separate hot water circuit to supply the household heating system. The cooled mine water would then flow back to the mine via the return loop.

The decentralised model would operate similarly however in this instance the water would circulate around the village in uninsulated pipes at the temperature that it came out of the mine and would be heated by individual household heat pumps.
Domestic units with thermal outputs of 3kW or 6kW were considered. Both the centralised and decentralised models would require installation of an insulated hot water tank, if not already present in the property. Initial findings suggest that the decentralised model would be the preferred option for the heat network; therefore, space for both a heat pump and storage tank would be required in properties connected to the network. This paper discusses the methodology adopted to provide a clear appraisal of the current heat demand of existing housing stock in Caerau, using a suite of investigative techniques, to enable correct sizing of heat pumps and the proposed heat network. The potential for retrofitting novel, renewable energy and demand management technologies that could complement the proposed district heat network are also considered.

3 Methodology

A range of complementary techniques were employed as part of a Holistic survey protocol to assess heat loss and the level of fabric insulation present, comprising: internal and external measured surveys; schedule of condition surveys; air permeability testing; and thermography tests. The information gathered was collated and used to calculate heat loss and heat transfer coefficient based on the methodology from the Standard Assessment Procedure (SAP) 2012, version 9.92 [14]. A visual inspection of the services within the properties was also made, with particular emphasis on the heating infrastructure and whether gas, electricity, or a combination of the two were used for internal temperature control. Where available, data from installed gas and electricity smart meters were collected to compare predicted heat loss figures with actual energy consumption. Many properties in the case study village were built in the early 1900s and the majority have been altered or extended since construction. Due to the non-destructive nature of the holistic survey protocol assessment, some assumptions had to be made as to the construction materials used in certain areas of the houses, as definitive identification was not possible.

4 Results

4.1 Condition survey

The condition survey involved an internal and external measured survey of each property and the production of dimensioned sketches of the floor plans and the elevations. A summary of the type of information captured in the schedule of conditions for one of the properties is as follows. Traditional Welsh three bedroom mid-terraced house of solid wall construction and with a single storey extension containing the bathroom and kitchen to the rear. Extension is of solid wall construction. Some thermal upgrades have been undertaken, with modern UPVC double glazed windows, and insulation applied to the attic spaces. Insulated plasterboard has been applied to the bathroom. Central heating throughout with a reconditioned condensing boiler and older style single panel pressed steel radiators. The condition of the property is generally just adequate. Property has notable damp and ventilation issues, leading to significant black mould growth in some areas of the property. Table 1 provides a summary of the property types surveyed, size and current levels of fabric insulation, i.e. loft, External Wall Insulation (EWI) and Internal Wall Insulation (IWI). The area of exposed external wall is a key contributor to the overall thermal performance of a building; from this perspective the properties presented fall into three categories based on the number of external walls; detached – four walls (property a), semi-detached and end terrace - three walls (properties b to d) and mid terrace – two walls (properties e to h). None of the properties surveyed met the recommended minimum level of loft insulation, which is 270 millimetre (mm) of mineral wool quilt (or equivalent) [15].

Table 1. Condition survey summary data

Property Title	Property Type	Number of Bedrooms	Floor Area (m^2)	Current Insulation
a	Detached	5	159	100mm loft
b	Semidetached	4	91	EWI, IWI & 200mm loft
c	End terrace	4	116	200mm loft
d	End terrace	3	87	100mm loft
e	Mid terrace	3	85	EWI to rear
f	Mid terrace	3	78	80mm loft
g	Mid terrace	3	92	Loft (partial)
h	Mid terrace	2	71	EWI & 80mm loft (partial)

All but one of the properties used a natural gas combination boiler as the primary source for space heating. The detached house had recently been fitted with an air source heat pump. In all cases the size of the central heating radiators would need to be increased in order to deliver heat effectively from a lower temperature, heat pump based system.

4.2 Air permeability

The air permeability tests were performed using a single fan blower door, in accordance with the Technical Standard L1 from the Air Tightness Testing and Measurement Association [16]. Tests were undertaken within the permitted conditions, i.e. less than six meters per second for the wind speed, all external doors and windows closed, all internal doors open, flues and air vents temporarily sealed and gas boilers switched off (if present). Calculated air permeability values are presented in Table 2. All properties surveyed were below the current maximum allowable air permeability value for dwellings in UK building regulations of $10m^3/h.m^2$ @50Pa [1].

4.3 Heat loss

The heat loss and heat transfer coefficients were calculated according to the standard assessment procedure [14], inputting data from the measured survey and air permeability tests results. Average annual values are presented in Table 2. Comparing the results of properties b, e and h with others in the same categories, the higher thermal resistance afforded by the retrofitted EWI is reflected in the lower average heat transfer coefficient and average heat loss parameters. Properties g and e had conservatories within the normally heated zone, which increase the thermal losses from these properties.

Table 2. Results of air permeability, average heat transfer and average heat loss parameter

Property Title	Air Permeability $m^3/(h.m^2)$@50Pa	Average Heat Transfer Coefficient (W/K)	Average Heat Loss Parameter (W/m^2K)
a	4.1	653	4.1
b	5.7	213	2.4
c	8.0	392	3.4
d	7.3	387	4.5
e	8.5	232	2.7
f	6.5	239	3.1
g	7.6	294	3.2
h	8.1	162	2.3

4.4 Thermography

Thermography was used to highlight major sources of heat loss and air leakage and also to identify any potential problems associated with ingress of damp and / or thermal bridging, and the SuRBe team at Cardiff Met University have much experience with thermography tests on dwellings since 2010 [17]. False colour thermal maps, or thermograms, were produced and thermally tuned prior to analysing the results. In order to conduct a meaningful thermographic survey certain environmental conditions need to be met. Best results are achieved when there is at least a 10°C temperature difference between the inside and outside of the building, there should be: no precipitation during the survey, surfaces should be dry, a maximum wind speed of 10 m/s, and no direct solar radiation on the surfaces for at least one hour prior to the survey. There is also a requirement to be cautious when interpreting thermograms where objects could be reflecting the night sky [18]. Both external and internal qualitative thermographic surveys were conducted to assess the thermal performance of the dwellings, particularly continuity of insulation; thermal bridges; sources of air-leakage at critical construction junctions; and moisture and damp within an element [19, 20]. Due to space limitations of this paper only one thermogram and associated digital image from a mid-terrace property is presented in Fig. 1 below. The property presented had EWI applied to the rear of the house but not on the dressed stone frontage. For internal surveys, any colours indicating extremities of cold entering the building are potential issues (dark blues and black). The thermogram in Fig. 1 shows considerably higher heat loss through the uninsulated, dressed stone exterior wall to the front of the property, above the window.

The coldest area is in the upper left hand corner above the wardrobe, where humidity levels may be higher due to a lack of air circulation.

Fig. 1a. Thermographic image of the interior of one of the test dwellings

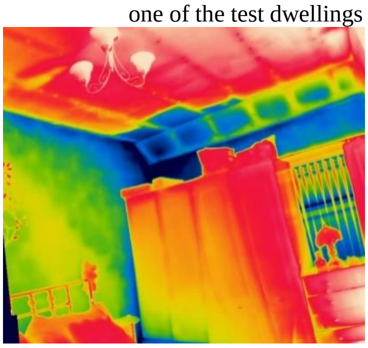

Fig. 2b. Corresponding digital image of the interior of one of the test dwellings

Heat loss along the raked ceiling at the wall junction may be the result of poor or missing insulation. Thermal bridging at the roof joists is also visible. Heat loss via conduction to the exterior wall and loft space is evident from the cool blue colour at the junction between the party wall (left), the ceiling and the front exterior wall. (Thermogram temperature scale 18^{o}C – 30^{o}C). Energy consumption

Using the heat transfer coefficient figures from Table 2 and assuming a maximum internal to external temperature difference of 24^{o}C (assuming an inside temperature of 21^{o}C and a worst case external temperature of minus 3^{o}C), the peak heat demand for the properties can be estimated. These are presented in Table 3. These values can be used to size the heat pumps required for a distributed heat pump network and the level of additional insulation that would be required to reduce the heat loads below a given threshold for connection to the network. The beneficial effect of additional insulation is highlighted by comparing the current peak loads for properties b and d, which are 5.1kW and 9.1kW respectively. Property b has EWI applied to two of the three exterior walls; the dressed stone front wall was not insulated, potentially due to planning restrictions. Internal insulation was also installed in the lounge. Property d had no EWI and minimal loft insulation. A calculation of the theoretical peak heating loads that could be achieved with a high degree of thermal intervention was simulated by adjusting SAP calculations to include triple glazing throughout the properties, 250mm of EWI on all external walls and 350mm of loft insulation. The results are presented in Table 3. The larger detached, semi-detached and end terrace properties which have more uninsulated external wall area, show the greatest improvement, as would be expected. These levels of thermal intervention are unlikely to be achieved to Welsh valley terraced housing where dressed stone frontages are an architectural feature. Additionally, space constraints where access around properties and in attic spaces would be reduced to unacceptable levels and rerouting of existing services may not be possible. Furthermore, economics: the costs rise linearly with increasing insulation thickness, while the net benefit diminishes. Similarly the thermal performance improvement of replacing good quality double glazing with triple glazing is small relative to the cost.

Table 3. Estimated peak heat load

Property Title	Average Heat Transfer Co-efficient (W/K)	Current Peak Heating Load (kW for ΔT=24ºC)	Peak Heating Load after Interventions (kW for ΔT=24ºC)
a	653	15.6	5.4
b	213	5.1	3.4
c	392	9.4	3.8
d	387	9.1	3.8
e	232	5.5	3.3
f	239	5.7	2.6
g	294	7.0	3.3
h	162	3.9	2.4

5 Discussion

By far the greatest opportunity for reducing the heat demand for space heating is to retrofit additional wall and loft insulation. The advantages of EWI as opposed to interior wall insulation include: reduced risk of thermal bridging, improved air tightness, thermal mass remains exposed to the internal space to aid control of summer overheating risks, less disruption to occupants, no loss of internal floor area, and internal fixtures and fittings do not have to be relocated [20, 23]. Achieving a complete covering of EWI at critical junctions to prevent all thermal bridging can be challenging, including: window and door reveals, wall to roof junctions, any projections such as porches and conservatories and where adjoining buildings meet (as illustrated in Fig. 2) [24, 25]. Thermal bridging can lead to increased heat loss and thus a reduction in the overall thermal performance, along with internal surface condensation due to localised lower surface temperatures [26]. To address surface condensation resulting from thermal bridging, occupants can either: increase the internal air temperature to raise the internal surface temperature above the dew point temperature of the air; or increase the rate of ventilation to reduce the dew point temperature of the air to below the dew point temperature of the internal surface [27]. However, with either, or a combination of these approaches, energy use will be increased in order to maintain comfort levels [28], which will undermine the overall effectiveness and purpose of the insulation. Several of the properties surveyed showed signs of damp. These presented as condensation on the internal surfaces of some external walls and black mould growth in the corners of certain rooms and behind furniture, where air movement was limited. Increasing ventilation improves indoor air quality and the wellbeing of occupants by providing more oxygen for breathing, removing exhaled carbon dioxide, diluting pollutants / odours and reducing moisture build up and associated damp and mould issues. The most obvious and common approach to increasing ventilation is to open a window, however this carries with it an energy and cost penalty, as cold fresh air enters the building at the expense of warm air escaping. Retrofitting EWI would be expected to reduce uncontrolled air infiltration, which should be compensated for by additional controlled ventilation. The air permeability test results for properties b and d, (5.70 and 7.27 $m^3/h.m^2$@50Pa respectively,

Table 2) demonstrate this. This was not the case for the two mid terraced houses which had EWI applied. In both cases poorly finished penetrations for services lead to higher air permeability figures than would have been expected. Based on a heat pump with 6kW thermal output and rated electrical power consumption of 1.6kW, the additional load on the local electricity network as a result of transferring the space heating load from gas to electricity would equate to 0.24MW for 150 connected homes, or 1.36MW for 850 homes. The impact on the electricity network and the carbon equivalent of the heating solution could be reduced through incorporation of local renewable energy generation and storage. The orientation of the streets in Caerau and the overall topography of the village, in a broad valley which runs approximately South West to North East, lends itself to solar energy generation. The roof area of a typical terraced residence in Caerau is sufficient to accommodate approximately 3kW (peak) of crystalline silicon Photo Voltaic (PV) panels. A system of this size would provide a predicted total annual generation of 2770kWh, based on historical climatic data for the region. Storing this energy for later use could lower grid stress by removing spikes in demand and offset utility costs, particularly if time of use tariffs were introduced. Other options, could include electrical storage in batteries; solar thermal generation, an effective means of supplying pre-warmed fresh air to a building; or 'Heat Batteries' which use excess electricity from PV generation to heat a phase-change material.

6 Conclusion

A holistic method for assessing household heating energy demand has been presented. Retrofit of thermal efficiency interventions to reduce the overall heat demand of pre-1919 solid wall properties to a level where a mine water-based heat network would be capable of provide the primary heating mechanism, were investigated. Complementary renewable solar energy generation and storage technologies that could further reduce heat pump load, offset additional stress on the local electrical distribution grid and alleviate household electricity bills were considered. In general, mid terraced houses have the lowest peak heat demand, followed by end-terraced/semi-detached and then detached properties; as would be expected with increasing exposed external wall area.

Tight control over the quality of detailing of any EWI needs to be exercised to avoid thermal bridging and water ingress, as observed in the condition and thermographic surveys. In particular, consideration should be given to extending the roof line to ensure a good and permanent seal at the interface between wall and insulation. A moisture permeable EWI may be more appropriate for solid walled buildings in order to avoid problems arising from interstitial condensation and subsequent dampness which could inadvertently degrade the property over time. Planning restrictions may preclude the installation of EWI and the use of solar generation panels on dressed stone frontages. Clear signs of dampness from a combination of water ingress and insufficient ventilation were apparent in several properties. Somewhat perversely, this problem can be exacerbated by the addition of EWI, which has the effect of reducing uncontrolled air infiltration and increasing temperature variations on internal wall through poor detailing. Appropriate measures to increase ventilation rates should be taken in tandem to ensure that, in striving for increased energy efficiency, the health and wellbeing of residents is not compromised. A combination of solar thermal air heaters and controlled ventilation could help to reduce the risk of condensation on cold surfaces. Orientation / planning restrictions may preclude the use of wall mounted panels on certain houses. There are a number of technical and economic challenges to enable the use of a mine water district heat network, however with careful consideration and selection of complementary technologies and close control over quality during installation the desired outcome could be achieved.

7 Acknowledgment

The authors would like to thank Bridgend Borough Council, the Engineering and Physical Sciences Research Council, Innovate UK, and the WG for the financial support of this work.

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