Energy Policy 36 (2008) 4544–4547

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

What is the relationship between built form and energy use in dwellings? ☆

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ARTICLE INFO

Keywords:
Domestic energy
Lighting
Space heating

ABSTRACT

Energy is used in dwellings to provide four services: space heating, hot water, lighting and to power appliances. This paper describes how the usage of energy in a UK home results from a complex interaction between built form, location, energy-using equipment, occupants and the affordability of fuel. Current models with standard occupancy predict that energy use will be strongly related to size and built form, but surveys of real homes show only weak correlations, across all types of dwelling. Recent research has given us insights into occupancy factors including preferred comfort, 'take-back' from thermal efficiency improvements, and patterns of electricity use. Space heating is on a downward trend and is low in new dwellings. Energy use for lights and appliances, which is only weakly related to built form, is increasing. Strong legislation, combined with low-carbon technologies, will be needed to counteract this trend. Future challenges discussed include increases in real energy prices and climate change mitigation efforts, which are likely to improve the existing stock. Challenging targets are now in place for new housing to move towards low or zero energy and carbon standards. In the longer term, dwellings will demand less energy. Alternatives to gas for space heating will be increasingly common, including ground source heat and local combined heat and power (CHP) from biomass, while electricity could come from a more decarbonised electricity system. However, these improvements must be set alongside a demand for many new homes, demographic trends towards smaller households, and a more holistic approach to overall carbon use including personal transport.

1. Introduction

Intuitively, one might expect there to be a fairly close relationship between the energy use of a home and its built form. But surveys of real homes show very weak correlations between energy use and built form, across all types. This paper considers some of the reasons for this and the current knowledge base, and looks to the future evolution both of the housing stock and of these research challenges.

First, it is useful to define what we mean by built form and energy use in homes. 'Built form' has a variety of meanings, but is used here to mean the type of dwelling (terrace, semi-detached house, bungalow, flat etc.) and its geometry, internal layout, floor area, construction (solid or cavity wall, timber frame, solid or suspended floor etc.), its insulation level and its immediate surroundings. Many of these are directly related to a building's age, through a combination of contemporary styles, construction methods and building regulations. 'Energy' is used here to mean the total energy used within and around the dwelling in the form of electricity, by the combustion of gas and other fuels, and from centrally supplied (district) heat. Solar gains to spaces are excluded. Though important, they are hard to quantify, cost nothing, have no direct environmental impact and are not part of the energy supply system. Ground source heat pumps are included only in terms of the electricity they use.

There are about 24 million homes in the United Kingdom. Of these 21.8 million are in England,[1] comprising 29% terraces, 27% semi-detached, 17% detached, 9% bungalows, 3% converted flats and 14% purpose-built flats (DCLG, 2007). So, unlike many countries, the vast majority of dwellings in the UK are houses—86% in England. The stock is also fairly old. In England, 39% predate 1944, 42% were built between 1945 and 1980 (when thermal standards were raised significantly), and 19% after 1980. It is estimated that around a third of dwellings which will comprise the 2050 stock have yet to be built, and that by the same date 75% of the current stock will still exist.

Recent decades have seen large changes in demographics and household structures, with a trend to smaller households with fewer children. According to DCLG (2008), in England in 2007, 64%

☆ While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

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[1] Statistics on housing are mainly collected separately for the countries of the UK.

0301-4215/$ - see front matter
doi:10.1016/j.enpol.2008.09.014

of households consisted of a family group, with 29% consisting of a single person (6 million people), and the remaining 7% consisting of more than one family, or multiple people not in a family group. With more divorce and a declining marriage rate, the definition of a family has become more complex. Only 22% of households consist of a couple with dependent children, while 7% consist of a lone parent with dependent children—so less than a third of households include children. Neither are households static. Many children spend weekdays with one divorced parent and some or all weekends with the other. Household structure is important. Larger households tend to use more energy, but in general energy use per head increases with decreasing household size.

Energy in dwellings is used for space heating, hot water, lighting and to power appliances. The actual amount of energy used for these tasks results from a complex interaction between built form, location, energy-using equipment, occupants and the affordability of fuel. According to Owen (2006), 83% of energy use in the home is accounted for by space and non-electric water heating, and the vast bulk of this is done by gas. The remainder is accounted for by electricity use for other purposes, including electric water heating.

The main measure of energy efficiency, for heating, hot water and lighting but not appliances, is the Standard Assessment Procedure (SAP). This is a rating of energy costs normalised by total floor area (BRE, 2005). The calculation also gives normalised carbon emissions. For new homes, there has been a mandatory rating against the Code for Sustainable Homes (DCLG, 2006) from 1 May 2008, but this will still use the SAP to obtain carbon dioxide emissions.

A SAP rating is independent of location, using average Midlands climate for winter heating, and also assumes a standard occupancy and heating pattern. It is intended as a rating for the dwelling, not for the combination of dwelling and household. The SAP algorithm uses the areas and thermal transmission of exposed elements, air infiltration rate, efficiency of energy systems, and types of fuel. Most of these are directly related to the age of a building and to built form. SAP ratings are on a scale from 0 (worst) to 100 (zero energy cost). The average SAP in England has improved from 42 in 1996 to 48 in 2005 and new homes score 80+. If households all behaved in a similar way, then the SAP would be a good predictor of energy use, and would indicate that energy use was strongly related to built form, albeit modified by local climate. But studies have shown the SAP is actually a poor indicator for individual dwellings, which demonstrates the large influence of the household.

2. Space heating and cooling

Heat is lost through the building fabric, and by air infiltration and ventilation. Fabric loss is directly related to the insulation levels and the external areas. While insulation levels depend on age and subsequent improvements, such as loft insulation, the ratio of external roof and wall area to floor area depends on the building type—terraced houses, with two party walls, have a lower ratio than semi-detached houses, while detached houses and bungalows have the highest ratios. It has always been assumed, quite reasonably, that no heat is lost through a party wall (i.e. the shared wall between two dwellings) if both dwellings are similarly heated. However, recent research (Lowe et al., 2007) has shown there can be very significant heat loss when thermal insulation is bypassed via uninsulated and unsealed party wall cavities. We do not understand even existing dwellings as well as we think. Another source of heat loss often ignored is thermal bridging at junctions, through lintels, timber framework etc. In the past this has led to over-optimistic assessments of thermal performance. This becomes more important as the thermal transmission (*U*-value) of building elements is reduced, as the bridging accounts for a higher proportion of heat loss. Most Northern European countries have built reasonably airtight dwellings for a long time, but in the UK we tend to build much leakier buildings, with a consequent waste of heat. The 2006 Building Regulations tighten up on both thermal bridging, through stipulating minimum standards, and on airtightness through pressure testing to meet minimum standards.

Models such as SAP tend to overestimate the savings from energy improvement measures, because they assume that standard heating patterns obtain before and after the measures. There is now strong evidence that many homes were heated well below this standard before improvement and that the improvements serve to raise internal temperatures (Oreszczyn et al., 2006) and hence improve comfort (and health). This often means a much smaller reduction in energy consumption than predicted, and this is known as ‘take-back’ or ‘comfort factor’.

Heating regimes vary widely between households, which partly explains the weak correlation between SAP and measured heating energy use. Though homes are generally getting warmer due to widespread central heating and better insulation, there is no evidence that people want substantially higher temperatures in occupied rooms than in past decades. Temperature monitoring of 14 modern, well-insulated homes in Milton Keynes in 2005, which had been previously been monitored in detail in 1989–1991, showed very similar temperatures for the two periods for the same outside temperature of 5 °C. Average living room temperatures had changed from 19.9 °C in 1990 to 20.1 °C in 2005, while average bedroom temperatures had declined slightly from 19.7 to 19.3 °C, though confidence intervals overlapped in both cases (Summerfield et al., 2007). Although the work was carried out in the same houses, many of the inhabitants had of course changed.

The traditional model used in the SAP standard occupancy pattern is of a well-heated living room at 21 °C, typically with a focal point fire, while the rest of the house is at 18 °C, during occupancy. But this ideal may no longer be appropriate for a house with central heating and reasonable insulation. Such homes tend to have more even temperatures throughout, as the Milton Keynes houses show, and many have no focal point fire. As bedrooms, in particular, become comfortable, there is a greater tendency to occupy them during daytime and evenings for recreation or work. This is likely to increase use of lights and appliances in these rooms. Larger homes and larger households, are also likely to lead to more diverse use of space.

Many homes have been extended, which is often a more cost-effective way of increasing living space than moving house. Conservatories have been particularly popular, low-cost additions. During the 1980s conservatories were seen as a beneficial passive solar design ‘buffer space,’ to preheat incoming air and reduce wall heat loss. But 90% of conservatories are heated, and they are often open to the rest of the house throughout the year. With large areas of glazing, they can be a major heat sink during winter. In fact, rather counter-intuitively, double glazed conservatories lose more heat from the house than those with single glazing. The latter are so cold that they tend to be shut off and not used as winter living space (Oreszczyn, 1993).

Domestic cooling is at present very rare in the UK, and most is in the form of portable units used occasionally in hot weather. Countries such as France have lived with a much warmer climate, possibly similar in some respects to a future UK climate, and also use little domestic cooling. However, new homes have been shown to have higher summer temperatures and more overheating. This is clearly related to their built form through insulation, thermal mass, windows and shading. Limiting overheating is addressed in the 2006 Building Regulations via the SAP in a very basic way, but we may need to pay more attention to solar shading and summer ventilation to cope with more summer heatwaves while avoiding mechanical cooling.

Unlike those in most countries, the vast majority of UK houses are heated by wet central heating systems fired by a natural gas boiler, which also provides hot water. Space and hot water heating demand is mainly translated to actual gas use through boiler efficiency. For older boilers this can be as low as 50%. All new boilers must be efficient condensing boilers with typical nominal efficiencies around 90%, although operational efficiencies are likely to be lower as they do not always operate in condensing mode. Another important factor is control. Replacing a boiler is likely to be accompanied by improved control, which further improves system efficiency. Since boiler life is 15–20 years, we can expect 75% of existing boilers to be replaced by 2020 (Owen, 2006).

3. Hot water

Hot water use has only a tenuous link to built form. It is largely dictated by the number of people in the home and personal preferences for bathing and domestic washing practices, modified by the efficiency and capability of the hot water system. Research in New Zealand has shown that gas hot water systems, which could deliver higher flow rates, resulted in much greater hot water use for showers (BRANZ, 2003). The trend towards en suite bath and shower rooms in modern housing is likely to encourage more frequent bathing. Hot water use is poorly understood, but is the subject of detailed monitoring in around 100 homes by the Energy Saving Trust (2008), which is due to report soon.

Solar hot water is probably the most cost-effective renewable technology for homes, far better than photovoltaics, and is arguably already economic for new build. For existing homes the payback is usually longer due to higher installation costs and the incompatibility of many existing systems. Current penetration is low but the market is growing. Clearly it is only practical where there is sufficient roof area, although an installation could be shared between several dwellings.

4. Lighting

Although lighting use can be estimated as a function of glazing and floor area (and hence built form), required lighting levels, internal finishes, hours of use and lamp efficiency, this approach ignores a host of factors relating to individual occupants. Research has shown that choice of fittings is strongly influenced by fashion and by TV style programmes, with lighting rightly seen as having a central influence on the internal ambience (Crosbie and Guy, 2006). Tungsten halogen spotlights are very popular, despite being inefficient, because of their small size and the bright white spotlight effect they produce. For standard fittings, compact fluorescent lamps (CFLs) are greatly superior to tungsten lamps in terms of running costs, but penetration remains low because of their higher capital cost, their slow warm-up (though this has improved), and their light output, which is of inferior spectral quality or quantity to a nominally equivalent tungsten lamp. How much of this difference is perceived and how much is actual is not entirely clear. Also, many light fittings are unsuitable for most compact fluorescents due to their greater length, and only special CFLs can be used with dimmer switches. The phasing-out of tungsten lamps (but not tungsten halogen lamps) should reduce consumption, but some tungsten lighting may be replaced with tungsten halogen. LED lighting outputs are very low at present, with efficacy (light output per unit of energy) similar to fluorescent lights. However, LED lighting is expected to become more efficient than fluorescents in the near future. It is highly flexible in terms of colour, control and the ability to use large numbers of small sources, for example linearly or as a screen. Such flexibility could partially or entirely negate the efficiency gains compared to current domestic lighting.

People vary widely in the level and type of lighting they prefer, even within households, as do their lighting practices, for example whether they turn-off lights when leaving an unoccupied room. Older people, brought up with electricity much more expensive in real terms, may tend to be more parsimonious than younger generations who may regard it as essentially free, but older people also need brighter light as sight deteriorates. So, although built form plays a part, lighting installations and personal preferences have a far greater influence on energy use.

5. Appliances

Appliances can be broadly divided into ‘white’ goods—large kitchen appliances for washing, cooking and refrigeration—and ‘brown goods’—TVs, stereos, etc., the anachronistic term dating back to the days when such items came in wooden cabinets. With an explosion of technology and the arrival of home computers, the more appropriate term ‘infotainment’ is entering the jargon to replace ‘brown goods.’ It covers devices used for both communication and entertainment, such as computers and TVs with two-way communication.

Comparing a 1970s household with a modern household, there are now vastly more items of electrical equipment, though many are used infrequently or use very small amounts of power. Owen (2006) lists 17 electrical items for a typical 1970s household and 46 for a modern household. Most homes, regardless of size or built form, now have a refrigerator, freezer, automatic washing machine, microwave oven, hob and oven (ovens and hobs sometimes use gas, with gas hobs more common than gas ovens). But larger homes with more kitchen or outbuilding space often either have larger appliances or more of them, particularly for refrigeration. Cooking is also shifting from central usage, such as cooking the family meal on the main cooker, to more individual usage such as individual meals heated in a microwave oven. Similarly in infotainment; the family TV or radio has been replaced by an array of bedroom TVs, computers, MP3 players, mobile phones with mains chargers, CD players, computer game consoles, etc. It is not clear to what extent the sheer quantity of devices relates to floor area and the number of rooms, although it does not make sense to have more than one TV in a room.

Research into usage patterns, power consumption or even just classifying all these devices is at an early stage (Marjanovic-Halburd et al., 2008). It is generally perceived that a great many such devices are left on standby when not in use, and that this accounts for a significant part of the measured increase in domestic electricity consumption. The evidence base is weak but research is beginning to explore this. Mandatory EU appliance labelling has been effective in improving the efficiency of many white goods, particularly for refrigeration and washing, but this has not been used for electronic goods. An EU version of the Energy Star system is available to rate computers and related equipment (EU, 2008). A much stronger regulatory approach, combined with low-energy technology, is needed to counter the generally rising trend in electricity consumption for electronics (Owen, 2006).

6. The future

The Government has a target to have all new homes 'zero carbon' by 2016, as set out in the Code for Sustainable Homes. We do not know whether this is achievable. But assuming current build quality problems can be solved, it seems likely that within around 20 years new homes will need minimal or no space heating, regardless of their built form. Solar water heating will also become widespread, supplying more than half of the hot water in most of the homes where it is installed. Thus space and water heating will be largely decoupled from built form for new homes. The scope and form of renewable on-site electricity generation is also clearly linked to built form. So far, photovoltaics have proved reliable but very expensive, while field trials of micro wind have shown that this is not viable for most housing: "Some rural installations could have costs of energy competitive with grid electricity. But it appears that in many urban situations, roof-mounted turbines may not pay back the carbon emitted during their production, installation and operation" (Carbon Trust, 2008). Around 100 of the estimated 165 domestic installations in the UK are currently being evaluated (Energy Saving Trust, 2008).

Real fuel prices (including taxes) are likely to continue rising in the coming decades because of an increasing commitment to climate change mitigation, concerns over security of supply as North Sea gas supplies are replaced by more remote and less politically secure sources, and a global shortage of fossil fuels that is already evident in rising prices. In the shorter term this will result in widespread improvement to older housing, mainly through loft and cavity wall insulation and perhaps solid wall insulation, and in more efficient heating systems. Microgeneration Stirling engine systems may have an impact, although current systems have a very low-electricity conversion rate of around 10% or less, so they need a large heating demand to be economic and are not suitable for well-insulated dwellings. In the longer term gas may cease to be a viable heating fuel. This would make ground source heat pumps run by electricity a possible but expensive (in installation terms) replacement. These already produce less carbon than a gas boiler. A decarbonised electricity supply using nuclear power, renewables, carbon sequestration etc. would reduce the carbon emissions even further. At present, biomass boilers are not viable for dwellings, but are popular as a low-carbon solution for larger buildings. In the medium term, localised CHP with biomass may be an attractive domestic option. Personal carbon allowances may be brought into play at some point, bringing domestic energy use into the sphere of overall carbon emissions.

7. Conclusions

The actual energy usage of a home results from a complex interaction between its built form, its location, the energy-using equipment it contains, its occupants and the affordability of fuel. Most energy use, and carbon emissions, are for space and water heating provided by gas. Households have a stronger influence on energy use than does built form. There are wide differences between similar dwellings, though larger dwellings tend to use more energy.

Research is beginning to address the complexities of the relationship between energy use, built form and households through more detailed surveys and monitoring, and by combining social science work with physical measurements.

Central heating has lead to more even temperatures throughout the home, and insulation has increased temperatures generally, but there is no evidence of a trend towards higher temperatures in occupied rooms for a given level of insulation. Home extensions, particularly conservatories, can increase energy use. Replacement of inefficient boilers can bring large energy savings.

Lighting will undoubtedly become more efficient as inefficient tungsten lighting is phased out. Electronic goods continue to proliferate, but appliance efficiency, again per unit, will improve and standby wastage is likely to disappear through technical improvements and legislation. This may halt or reverse the current 1% per annum rise in domestic electricity use.

Climate change mitigation, security of supply concerns and world demand for fossil fuels are likely to result in higher fuel prices and further measures to improve the efficiency of both the existing and new build stock, at least for space heating. In the longer term, gas may be replaced by electrical or other solutions for heating.

But against this must be set the plans for three million more homes in the UK, and demographics which continue to reduce household size, while demand rises for more individual lifestyles and hence for more appliances. This could mean reduced energy use per home while overall domestic energy use continues to rise. Finally, energy used in the home only accounts for a small proportion of total domestic carbon emissions, which also include energy used for food, waste, transport etc. For example, building more energy-efficient homes on the urban fringes could generate increased car use and wipe out reductions in home energy use compared to that in older houses within easy reach of the city centre.

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