Thermal Energy Supply and Demand in the UK Domestic Sector

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FOREWARD

The Fabric integrated thermal storage in low carbon dwellings project (FITS-LCD), funded by EPSRC seeks to generate the technical and economic concepts, undertake prototype technical demonstrations, develop software models and assess user acceptability, for the effective deployment of fabric-integrated thermal storage in dwellings and communities within the context of wider low-carbon energy networks.

The work brings together a multi-disciplinary team drawing from the disciplines of Architecture (Mackintosh Architectural Research Unit, Glasgow School of Art), Economics and Policy (Centre for Process Systems Engineering, Imperial College), Mechanical, Electrical and Software engineering (Energy Systems Research Unit, Institute for Energy and Environment, University of Strathclyde), Building Physics and Materials Engineering (Centre for Innovative Construction Materials, University of Bath).

This document covers thermal energy demand in the UK domestic sector, looking at levels of demand, where and how thermal demand is supplied and how demand may change into the future.

This is the first of a series of background reports produced by the FITS-LCD research partners, which sets the context for the integration and application of domestic thermal energy storage in future energy networks at all scales.

BACKGROUND – DOMESTIC SECTOR ENERGY USE

In 2014, UK final energy consumption stood at 135.3 Mtoe (1573 TWh), the lowest level recorded since the 1970s (DBEIS, 2016a). Heat accounted for over 45% of UK final energy demand (DBEIS, 2016a); with domestic sector heat use (space heating and hot water) accounting for around 24% of final energy demand. The residential sector in the UK accounts for 23% of the UK's greenhouse gas (GHG) emissions (DECC, 2016). The average energy consumption of a UK household is 18.6 MWh per annum and average CO_2 emissions are approximately 4.4 tonnes per household. Around 82% of domestic energy is used for either space heating or hot water heating. Energy use for appliances, lighting, cooking and clothes washing, accounts for the remainder. However, the use of electricity has increased over 16% since 1990, peaking in 2010, and is becoming an increasingly important component of domestic energy use and expenditure as space heating demand falls (DBEIS,2016a).

The bulk of domestic heat is provided by gas central heating (approximately 76%), with 8% from electricity, 8% from oil and the remainder from a variety of fuel types including coal and renewables (DBEIS, 2016a).

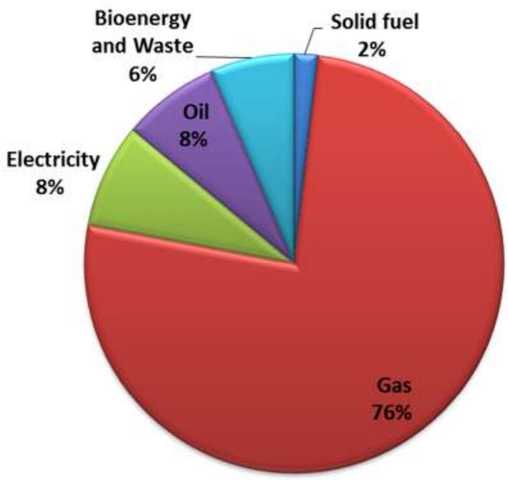

Figure 1: Breakdown of UK domestic thermal energy supply by fuel type (DBEIS, 2016a).

The UK domestic Sector

As of 2014, the total UK housing stock was some 28 million dwellings (DCLG, 2017), a figure which has been rising steadily over recent decades. For example in 1970 there were only 18 million dwellings. The current number of new homes built each year averages 150,000 dwellings (DCLG, 2016a), this figure far outstrips the number of dwellings demolished each year, which is less than 20,000 (DCLG, 2016b). Overall, the rate of turnover of the stock is lower than 1% per annum. This indicates that if significant energy efficiency improvements are to be achieved, then there need to be retro-fitted improvements to the existing stock in addition to new build housing: at current rates of change around 80% of the housing stock in 2050 will comprise buildings in existence today (Hinnells *et al*, 2007).

Across the housing stock there are a broad range of dwelling characteristics, with many different ages, sizes and shape of building, with the proportions of basic types shown in Table 1, which also indicates typical floor area and heat loss rating.

Type	Detached	Semi-detached	Terraced	Flat
% of housing stock	25	26	28	21
Average floor area (m2)	151	93	83	58
Average heat loss (W/°C)	342	265	235	167

Table 1: Percentage of UK dwellings by main type (Palmer and Cooper, 2013), average floor area by type (DCLG (2013) and SG (2014a)), and heat loss parameter by type (Utley and Shorrock, 2008)

The age of a dwelling (Table 2) has a very significant impact on energy performance as it dictates the constructions used (particularly the external wall construction) and the air leakage characteristics; generally, the older the dwelling the poorer its energy performance. As would be expected with the low rate of housing turnover the vast majority of UK dwellings are over 25 years old.

Year Built	Pre 1918	1918 – 1964	1965-1990	1991-1997	Post 1997
%	20.8	36.3	29.4	5.0	8.5

Table 2: Percentages of UK dwellings by age (adapted from Palmer and Cooper, 2013)

Dwellings can be divided into three time periods where specific external wall types predominated. Prior to 1918, buildings had solid external constructions. Post-1918, wall constructions with cavities emerged featuring an inner and outer layer of brickwork separated by a ventilated cavity (typically 60mm in depth); many of these cavity constructions have been altered over time to improve energy efficiency, such that by 2011 64% of houses with an external cavity wall construction had had cavity insulation installed (Palmer and Cooper, 2013). Finally, as building standards improve, energy-efficient timber frame constructions are becoming more popular in post-1997 dwellings.

A further factor that dictates the need for space heating is the leakage of outside air into dwellings; this is dependent on many factors including the construction and age of the building (in general, the older the building the 'leakier' its construction), the type of glazing, exposure to wind, and the use of windows and installed services such as chimneys, flues and ventilation systems. However, on average, the construction air tightness of dwellings has improved over time: decreasing from around 0.8 air changes per hour[1] in the 1950s to 0.5 for houses built in the 1990s (Johnston *et al*, 2004). The emerging passive house standard (discussed later) has target construction leakage rates of better than 0.04 air changes per hour (PHI, 2012).

Turning to other important fabric elements and improvements that impact upon energy use; the glazing present in a particular house is dependent upon the age of the dwelling, but also on whether the owner has invested in fabric improvements. Before the mid-70's, dwellings in the UK were constructed with single-pane glazing. However, double-glazing ownership has increased from around 8% of households in 1978 to 75% of housing having full double glazing by 2011 (Palmer and Cooper, 2013). Triple glazing is also beginning to appear in the housing stock; however reliable figures as to its uptake are yet to appear. Around 97% dwellings having some form of loft insulation, with around 47% of houses having more than 150mm of insulation (Palmer and Cooper, 2013).

Current UK Domestic Thermal Demands

Analysis of the UK housing stock indicates that the average energy efficiency (average SAP rating[2]) for all dwellings in the UK is around 61 (DBEIS, 2016a). The SAP rating is predominantly a measure of the energy required to heat a dwelling. It should be noted that energy consumption will differ for identical houses in different regions because of climatic differences. For example, a house in Northern Scotland, in an average year, will require nearly 45 % more energy to maintain a given temperature than the same house in the milder climate of the South West of England (Utley and

[1] An air change per hour is defined as: volume of outside air leaking in to the dwelling over 1 hour (m^3) divided by the heated volume of the dwelling (m^3).

[2] The energy efficiency of dwellings is indicated by a standard assessment procedure (SAP) rating; SAP is a calculation which uses information on the constructions and energy systems present within a dwelling to produce a value between 1-100, which indicates the notional energy performance of a dwelling. A SAP rating of 1-20 indicates exceptionally poor energy performance. A SAP rating of 100 indicates zero energy costs. A SAP rating of 100+ indicates that a dwelling would be a net energy exporter.

Shorrock, 2008). Figure 2 shows the estimated SAP rating of the UK housing stock and illustrates the general improvement in energy efficiency since 1970.

Focusing specifically on the heating requirements for dwellings, Table 1 includes the heat loss coefficient broken down by the different housing types (Utley and Shorrock, 2008). This is the heat loss per ^{o}C temperature difference between the interior and exterior of the building: it includes both losses through the fabric and losses due to infiltration of outside air.

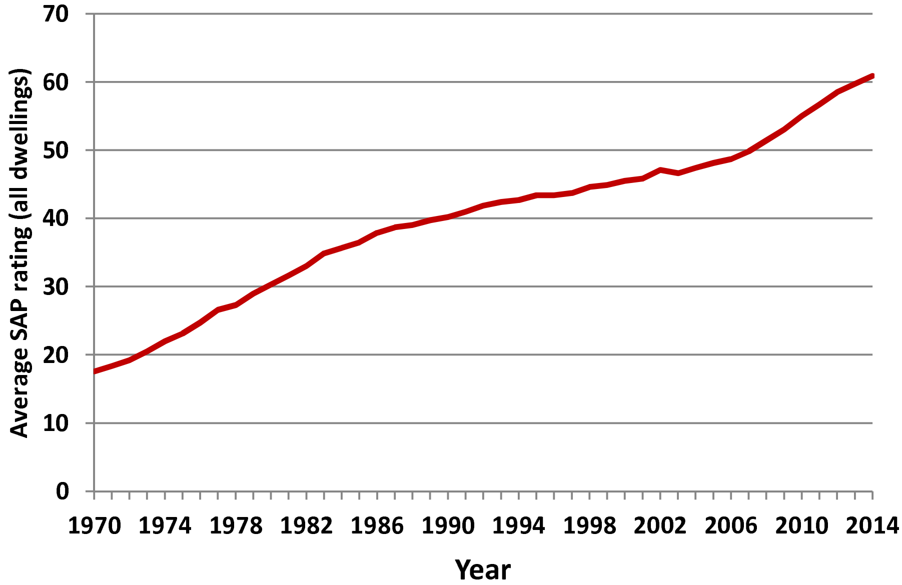

Figure 2: Average SAP rating of UK housing (DBEIS, 2016a).

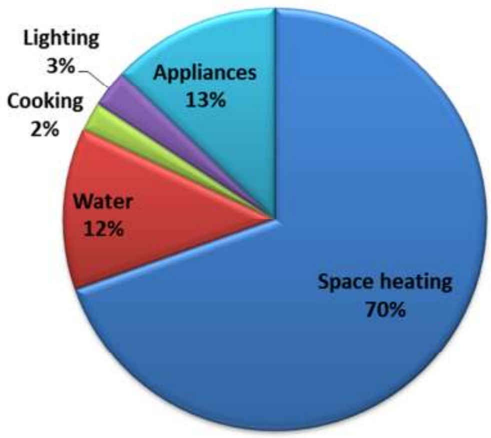

Figure 3: Breakdown of energy use in UK dwellings (DBEIS, 2016a).

Space Heating

Space heating remains the primary demand for energy in UK dwellings (see Figure 3), accounting for around 70% of demand. Indeed, the proportion of energy required for space heating has increased steadily (it accounted for 59% of demand in 1970 (DBEIS, 2016a)), despite the improvement in the energy efficiency of dwellings.

The amount of space heating required for a specific dwelling is dictated by many factors including the quality of the building fabric (as discussed previously) but also the number and behaviour of the occupants, the size of the dwelling, heat gains from appliances and the climate (external air temperature, solar heat gains, etc.). However, the main reason for the increasing significance of space heating appears to be that whilst the energy efficiency of dwellings has improved, so have expectations of thermal comfort. For example, in 1970 the average indoor air temperature in centrally heated homes was 13.7°C, this has risen to 17.7°C today (Palmer and Cooper, 2013).

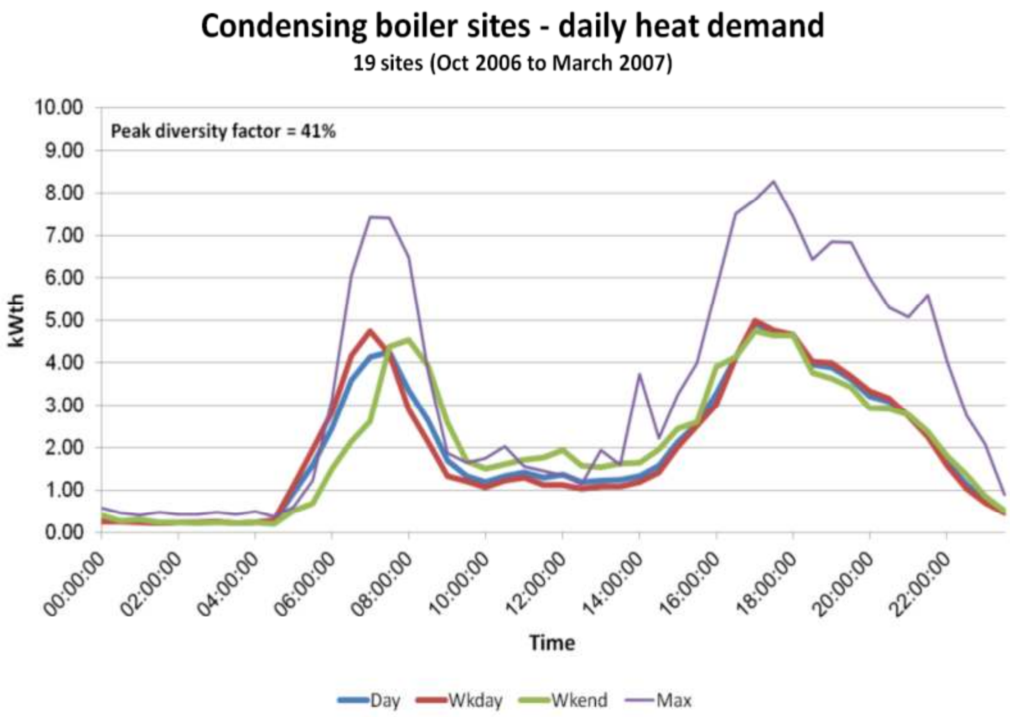

Figure 4a: Daily variation in space heating demand (from Sansom, 2015)

Figures 4a and 4b show characteristic daily and seasonal space heating demands in UK dwellings. Figure 4a shows the average daily demand profile from 19 households with gas boilers (Sansom, 2015), with distinct peaks in the morning as the building fabric warms up from an overnight shutdown and a second peak in the early evening coinciding with returning to the dwelling from work and other daytime activities. Figure 4b shows the variation in demand over the course of the year, with little or no space heating requirement in summer and the bulk of demand concentrated in winter. Note that in this case the regular peaks in daily demand evident in the graph correspond to weekends, when the dwelling is more likely to be continuously occupied against intermittent occupation during weekdays.

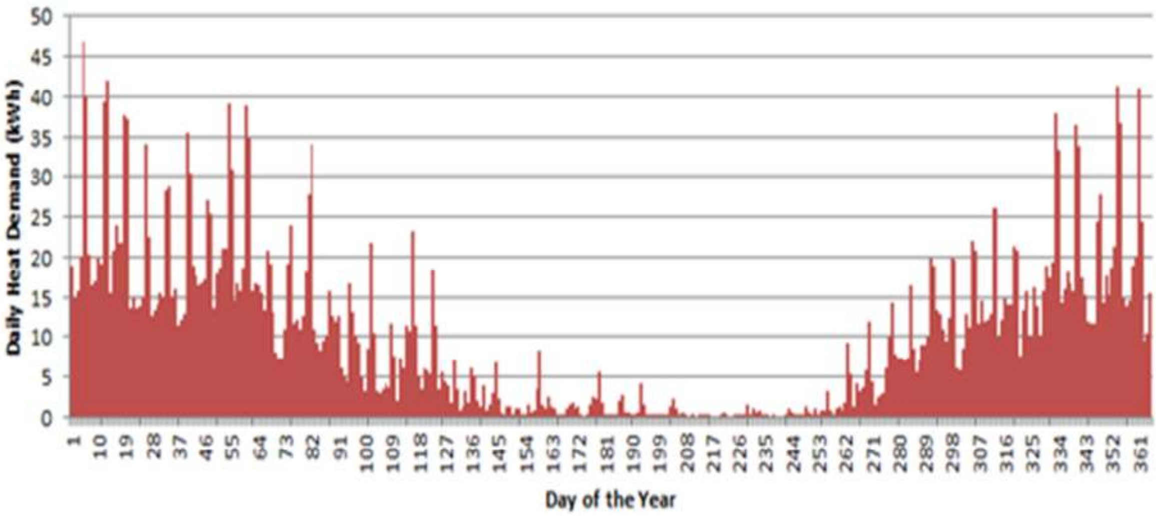

Figure 4b: Typical seasonal variation in space heating demand.

The primary source for space heating in UK housing is a boiler (typically gas or oil-fired), which features in 90% of dwellings (DBEIS, 2016a). Electrical storage heating accounted for around 6% of space heating, however this heating type is far more prevalent in low income housing.

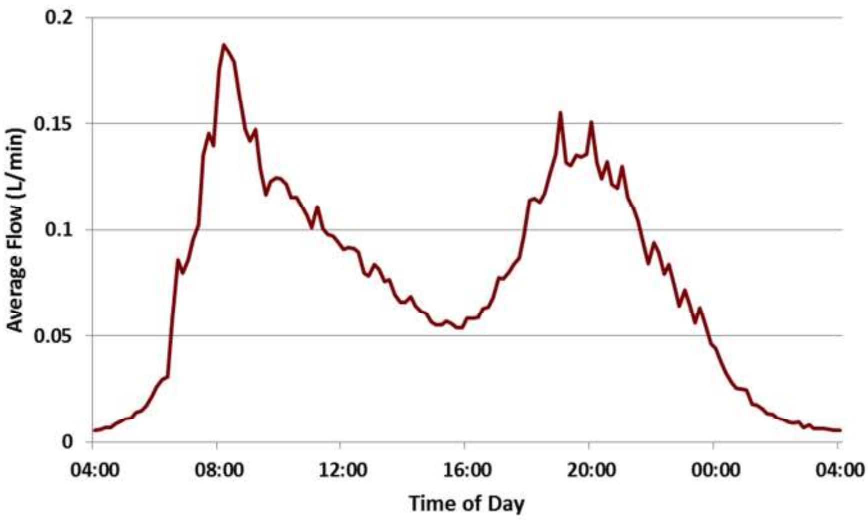

Figure 5: Average variation in hot water demand (based on EST (2008) data)

Hot Water

The average level of hot water consumption per-household in the UK has been determined to be 36 litres plus 25 litres per person (EST, 2008), resulting in an annual energy consumption for hot water of some 2.3 MWh for a 4-person household. Hot water demand accounted for 15% of domestic energy demand in 2015 (DBEIS, 2016a), a significant fall from 29% in 1970 as a result of more efficient generation and changing behaviours.

A detailed review of a comprehensive usage dataset (EST, 2008) shows that hot water use is a combination of low volume demands (to 3 litres), such as handwashing, that account for c.50% of uses, medium volume demands (3-15 litres), such as dishwashing, that account for 34% of draws, and the remainder high volume uses associated primarily with baths and showers. Timing of low volume uses follows typical occupancy patterns with medium and high volume uses more concentrated in morning and evening periods. This is highlighted by the overall average hot water use profile from the EST data shown in Figure 5.

A typical draw profile (based on 5-minute averaged flow) is shown in Figure 6 based on a household with a 100 litres/day average use (equivalent to a typical 2-3 person household) (Knight and Ribberrink, 2007); this illustrates the very sporadic nature of hot water draws and characteristic morning and evening clusters of higher demand activity. Household energy uses for hot water is further complicated by the mix of electric- and hot water circuit-supplied showers that determines the energy source for this potentially significant energy demand.

There is little seasonal variation in hot water demand; however, Jordan and Vajen (2005) argue that there is a sinusoidal variation in the daily volume of draws, with a reduction in hot water use in summer. Further, the change in ground temperature has a slight effect on the energy required for water heating as the resulting cold water feed water temperature changes throughout the year.

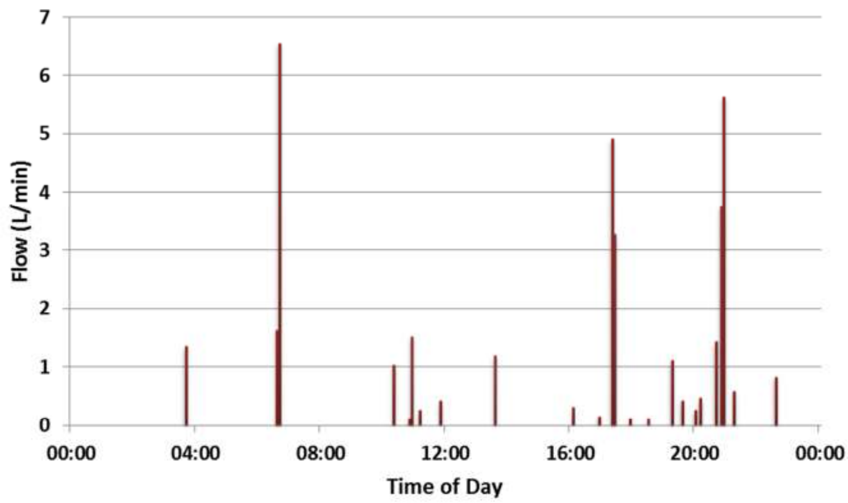

Figure 6: 'Typical' European daily hot water draw profile for 2-3 Person household (Knight and Ribberink, 2007).

Electrical Demand

The typical electrical demand in a UK dwelling in 2015 was some 3.9 MWh per annum, some 17% of the total energy demand (DBEIS, 2016a), an increase from 13% of demand in 1970. However, given that the price of electricity per kWh is more than three times higher than the price of gas, the amount paid by consumers is a significant portion of their total energy bill (DBEIS, 2016b). The breakdown of domestic electrical demands is shown in Figure 7.

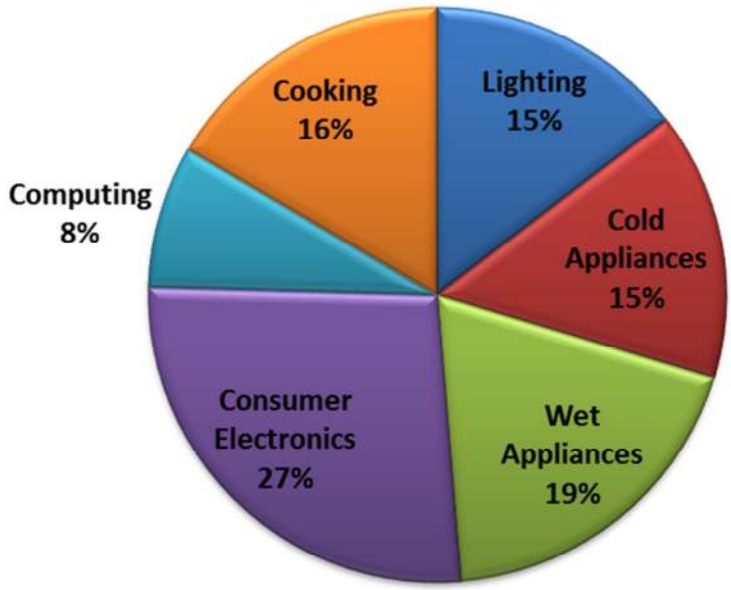

Figure 7: Breakdown of electrical demand in UK domestic sector (DBEIS, 2016a).

Figure 8 and b shows average measured electrical demand for UK households without electric heating for a winter and summer month (DECC, 2012a). As with the heating and hot water demand profiles, the electrical demand exhibits significant temporal variability, with morning and evening peaks evident, particularly in winter. Significant use variations of up to an order of magnitude are also seen for households with similar characteristics.

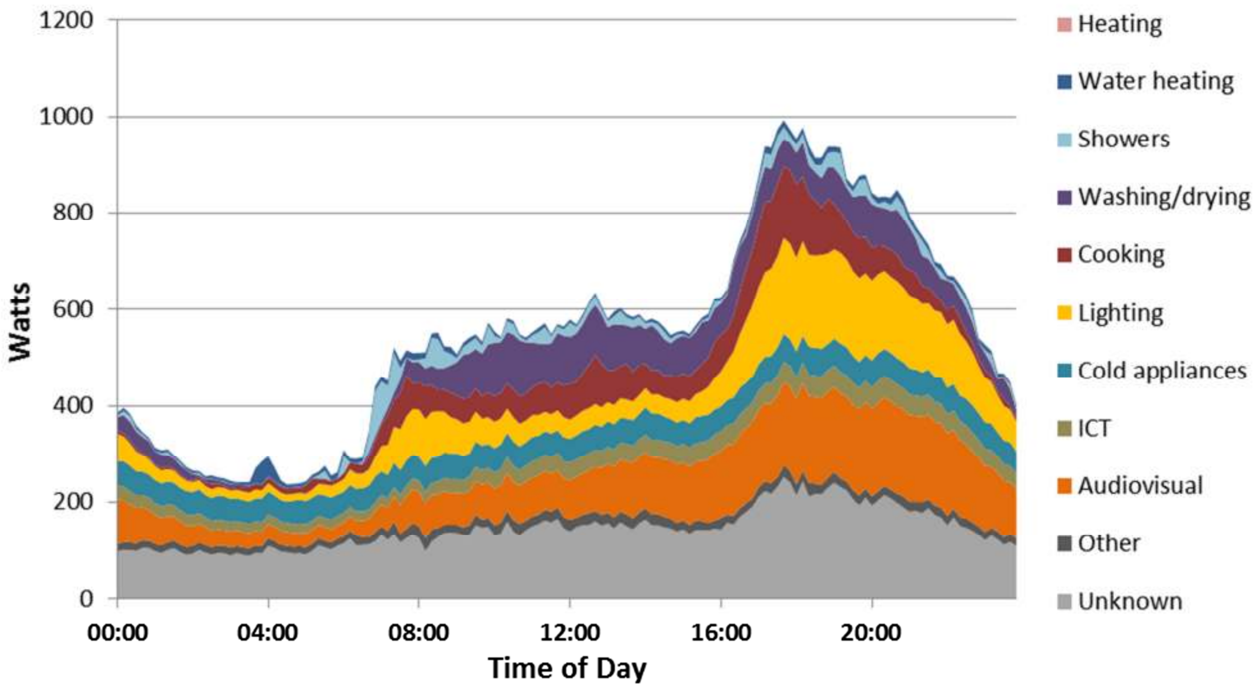

Figure 8a: Average winter (January) electrical demand for households without electric space heating (DECC, 2012a).

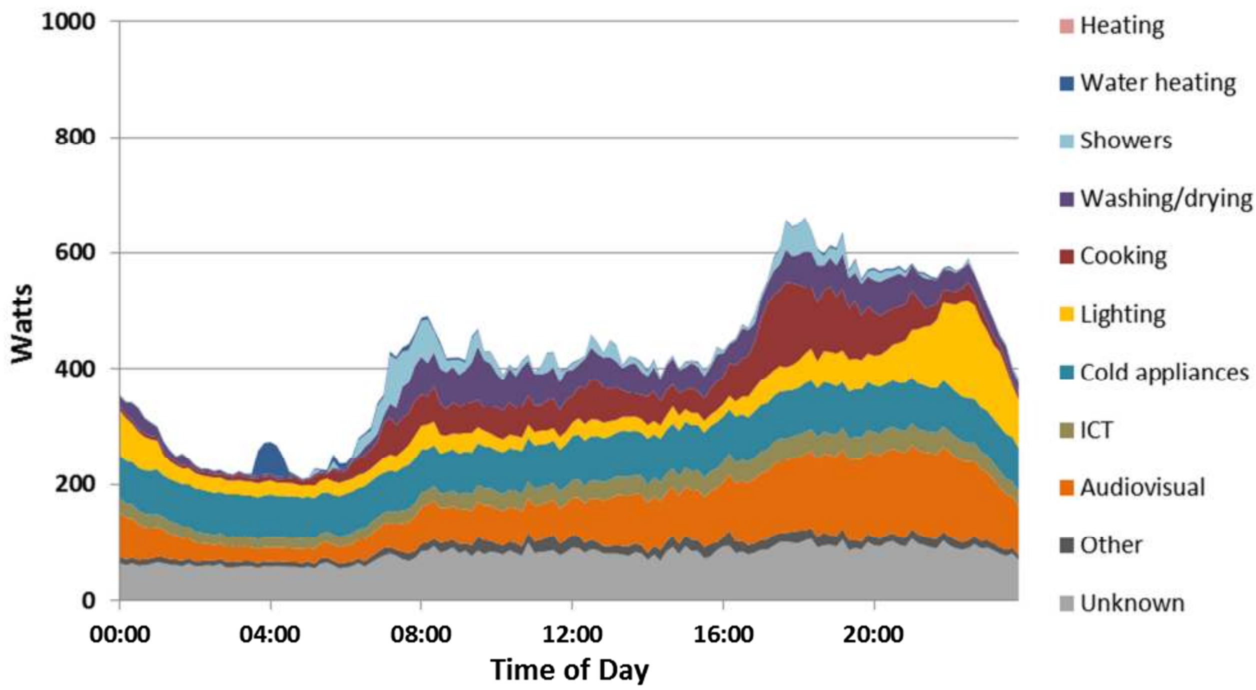

Figure 8b: Average winter (July) electrical demand for households without electric space heating (DECC, 2012a).

Figure 8 and b is typical of the situation where only appliances and lighting require electrical power, with space heating and hot water demand met by a gas boiler. Approximately 9% of thermal energy demands in UK housing are met using electrically-powered devices including storage heating, direct electric heating and heat pumps (DBEIS, 2016a). In these cases, the winter electrical demand would be significantly greater than is shown above. It should be noted that many consumers with electric heating actively manage their own demand; end-users on variable price tariffs such as Economy 10 (ECON10, 2017) typically adjust the operating times of opportune loads such as dishwashers and washing machines to take advantage of lower electricity prices during off-peak periods.

THERMAL ENERGY DEMAND DRIVERS

Background – Legislation and Building Regulations

A key mechanism for reducing the energy demand for both new build and existing UK dwellings has been housing and housing-related policy and legislation. Recent years have seen an escalating demand for action on global warming particularly from pan-national bodies such as the United Nations and European Union (EU), (e.g. UN (1998); EU (2002); EP (2010); UN (2015)). Moreover, increasing competition for fossil fuel resources and escalating energy costs are creating an environment for radical changes in legislation.

Historically, building energy efficiency legislation in the UK has lagged behind many of our European neighbours. For example, in 1977 the Danish BR77 standard set out energy efficiency levels not seen in the UK until after 1997 (Kjaerbye et al, 2011). Specific UK building regulations relating to energy use only emerged following the first energy crisis of 1973. However, the late '90s saw a dramatic shift in energy-related legislation for housing across the UK, with regular updates to the energy-related performance requirements within building regulations between 1997 and the present.

A key legislative milestone has been the adoption into legislation of the EU 2002 Energy Performance in Buildings Directive (EPBD) (EU, 2002) which required energy performance assessment, energy rating and the identification of cost effective improvement measures for all buildings at the point of sale or rental. The EPBD also required member states to establish minimum performance standards for new buildings and improve these standards at least every 5 years. In support of the implementation of the EPBD, the European Committee for Standardisation (CEN) established or revised a raft of related standards. A total of 30 European (EN) and 24 international (EN ISO) standards were drafted or updated including those relating to minimum energy performance levels, calculation methods and inspections of heating and cooling equipment (Roulet and Anderson, 2006). Since January 2009, all EU member countries have implemented the requirements for performance assessment, energy rating and improvement identification in compliance with the original EPBD.

In 2010 a further update of the EPBD was passed by the EU (EP, 2010); this EPBD2 legislation requires that member states implement 'nearly zero energy' standards for new or refurbished buildings by 2020 (2018 for public buildings). A nearly zero energy building (nZEB) is defined as: "a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (EP, 2010). There is no single, defined

EU-wide target for nZEBs, with different requirements defined on a country-basis in accordance with local regulations (BPIE, 2015).

In Nov 2016 the EU released the 'Clean Energy for All Europeans' package, which incorporated a proposed review of the EPBD. The preferred option for an updated EPBD is based on the same framework but with additional requirements to address specific current problem areas, such as inconsistent uptake by members and low inherent renovation rates for existing buildings (EC, 2016).

The implementation of standards relating to the EPBD has been done through country-specific legislation developed by each member state, rather than on a Europe-wide basis. In the UK, Buildings Standards have been the primary tool for the introduction. Building Standards are devolved to the regional legislatures, although in many cases the same or similar policies are used. The energy performance elements of the original EPDB were implemented in tandem with general amendments to Building Standards in England and Wales (ODPM, 2006) and in Scotland (SBSA, 2007).

In addition, England, Wales and Northern Ireland introduced the Code for Sustainable Homes (CSH) in 2006 (DCLG, 2008), which introduced a ten-year process of development and innovation, with a final aim of an achievable regulatory zero-carbon housing standard by 2016. In 2011, the definition of 'zero carbon' was clarified as relating only to 'regulated emissions' such as heating, hot water, and lighting, and not to plug loads. However, in 2015 the policy was scrapped with no further improved energy efficiency targets planned beyond those introduced in the 2013 Building Standards. In Scotland, a similar process was undertaken from 2007 with stepped carbon emission improvements for Building Standards updates planned with a similar zero carbon target by 2016/17 (Sullivan, 2008). The target date has since been postponed with less stringent than planned emissions reduction targets included in the 2015 update.

As discussed further below, the impact of the UK leaving the European Union and the individual attitudes of the devolved UK governments to retaining the requirements of some or all European directives if this occurs are not clear at this time. The current policy basis for England, Wales and Northern Ireland does not align with the EPBD 'zero carbon' requirements and the future direction for policy in Scotland has not been clarified.

Improving Energy Efficiency: New Buildings

The EPBD has been implemented in the UK through revisions to the building regulations which mainly apply to new buildings, with similar approaches initially taken by the devolved legislatures. The energy standards for new buildings have been improved in iterations of all UK building regulations implemented in both 2007 and 2010; each of these iterations has targeted approximately a 30% reduction in calculated carbon emissions compared to the previous. The 2013 update that applied outside of Scotland targeted a further 6% reduction on the 2010 basis for new buildings. The 2015 update to the Scottish regulations targeted an equivalent 21% reduction from 2010. To achieve the carbon emission targets, the building regulations have increasingly encouraged the adoption of 'renewable' technologies including heat pumps, solar thermal and PV and made it increasingly difficult to achieve compliance with conventional electric heating due to the high cost and carbon factors associated with electricity without these renewable technologies.

Whilst the EBPD and building regulations stipulate minimum energy performance standards, there are many Government and industry initiatives that encourage the development of buildings that go beyond these minimum regulatory standards and closer to the targeted future regulatory standards, such as 'nearly zero energy'. Examples include the CSH as outlined, and, in addition, 'Ecohomes' (BREEAM, 2012) and Passivhaus (PHI, 2017) standards for dwellings, and the 'BREEAM' (BREEAM, 2012), LEED (USGBC, 2017) and Passivhaus standards for non-domestic buildings (PHI, 2017).

PassivHaus has been an important programme for Europe-wide standardisation and a step-change in energy performance in buildings. Since the late 90's the EU has funded projects for the development, validation and dissemination of the Passive House standard for intended adoption across the EU. The 'cost effective passivhaus for EU standard' (CEPHEUS) project ran from 1998 to 2001 , resulting in approximately 250 dwellings being built to the Passive House standard and then monitored across 5 central and northern EU countries; this showed a 90% reduction in space heating energy demands compared to standard buildings (Schneiders, 2003).

To-date, over 60,000 passive houses have been constructed around Europe (iPHA,2016). The basic requirements for a Northern European Passive House are: very high levels of insulation and high-quality building construction (thermal bridge free, air-tightness of construction better than 0.04 air changes per hour); high-performance glazing; a high efficiency ventilation system with heat recovery (MVHR) (heat recovery > 90% and fan power < 0.45Wh/m^3); ventilation openings, thermal capacity and shading designed for comfortable summer temperatures; and high efficiency appliances and lighting. To achieve Passive House standard, the calculated heating and cooling energy demand (calculated assuming low levels of internal gains and a worst case local climate) must be less than 15kWh/m^2 per year and the primary energy demand less than 120 kWh/m^2 per year.

The UK participated in several EU projects aimed at dissemination of the Passive House standard which is currently being promoted in the UK through the UK Passive House Trust (UKPH, 2017). Note that there are low energy building standards in existence or in gestation throughout the world. Examples include the pioneering R-2000 standard in Canada (NRCan, 2005) and MINERGIE-P in Switzerland (Minergie, 2012); these other standards are largely in synergy with the Passive House approach. The 'net zero carbon' design basis in the UK CSH (DCLG, 2008) also incorporates some of the Passive House approaches to energy use, while also focusing on other environmental aspects, such as water efficiency and waste.

Improving Energy Efficiency: Existing Buildings

The building regulations have historically been targeted at new buildings, but it is increasingly being recognised, as addressed by the 2016 EPBD review, that the existing building stock must be tackled if emissions targets are to be met.

Improvements in existing building stocks have been the focus of some recent Government legislation and policy initiatives aimed at reducing energy use, carbon emissions and fuel poverty. Registered Social Landlords and Local Authorities providing for the rented sector have had to comply with the Home Energy Conservation Act (HECA) (HMSO, 1995) and more recently Decent Homes (DCLG, 2006). Both pieces of legislation set minimum standards for properties based on the calculated energy performance. The result is that social housing has a significantly higher SAP energy efficiency rating than private housing (DCLG, 2016c). In Scotland, the Scottish Housing Quality Standard required that all social housing met an enhanced standard, including energy performance, by 2015 (SG, 2015), and this has been further extended by the 'Energy Efficiency Standard for Social Housing' (SG, 2014b), which requires minimum SAP ratings of around 70 to be achieved by 2020. These requirements on social landlords have driven the uptake of improvement measures such as insulation, improved glazing and heating systems. However this sector also includes many so-called 'hard to treat' properties which may be off the mains gas grid and have construction type or historical significance meaning that standard low cost upgrade measures such as cavity wall insulation or gas boiler upgrades cannot be applied. These properties often require the adoption of technologies such as heat pumps or biomass boilers to meet the standards.

The privately owned and private rented sectors have not historically been subject to legislation but rather the improvement of this stock has been encouraged through various Government supported schemes encouraging upgrades to insulation, heating and hot water systems, lighting, equipment and appliances. These include the Green Deal program which ran from 2012 to 2016, providing loans and, subsequently, grants to perform accredited improvements, with limited success. From 2018, private rented properties will be required to have a minimum Energy Performance Certificate (EPC) with an 'E' rating for new contracts and this will apply to all private rented properties from 2020. It has also been suggested to extend this requirement to private property sales.

Improvements to the existing UK building stock have, in part, been financed through the Government's requirements on power companies to achieve significant carbon emissions reduction targets (CERT) (DECC, 2012b) through energy efficiency measures applied to supplied dwellings or be subject to penalties. These schemes were badged the 'Community Energy Savings Programme' (CESP) from 2009 to 2012 and are now the 'Energy Company Obligation' (ECO). The allowed improvements funded under ECO include insulation measures, heating systems and renewables (heat pumps, solar thermal and PV). More than 65,000 dwellings were improved under the CESP with the majority of measures being insulation and conventional heating system upgrades, there was also the installation of almost 6000 PV systems (OFGEM, 2017a). Under the ECO scheme, by November 2016, over 1.6 million households had received improvement measures, primarily either insulation or boiler replacements (DBEIS, 2017a). The ECO scheme, initially planned to end in March 2017, has been extended to September 2018 with the primary focus on reducing energy costs for fuel poor households.

Future Trajectory of Legislation

The poor economic conditions prevailing in the UK from late 2008 and recent changes in Government policy have resulted in a slowdown in the drive for both energy efficient housing and a cut in the financial incentives for microgeneration (e.g. the UK's Feed-In-Tariff has been significantly reduced and access restricted, the Renewable Heat Incentive was delayed, and the CSH, with corresponding 'near-zero-carbon' target', was first relegated to a voluntary standard for housing developers and then scrapped).

From a UK perspective, therefore, the future direction is uncertain with regard to the degree of obligation to European building energy directives if the UK leaves the European Union, and to the direction and timing of future revisions to the energy performance requirements of Building Standards. In a wider European context, however, it is clear from both existing and proposed directives that the pressure to improve the energy performance of buildings will continue to increase.

Hence, in assessing the potential energy demand of future dwellings, especially towards 2050, technical and economic drivers rather than legislative limits may dictate levels of demand, at least in new build housing. Increasing fuel costs and reductions in the cost of microgeneration and building fabric upgrades allowing for demand reduction initiatives to be cost effective without additional incentives or obligations. In retro-fit housing the picture is less clear, with many other factors, including the basic fabric of the dwelling and ability to implement changes (e.g. improvements to older buildings are subject to planning legislation), affecting the eventual energy performance. It is also worth bearing in mind that the majority of buildings in 2050 are currently in existence, and that older buildings are disproportionately impacted by rising fuel costs, so the potential for retrofit to improve energy efficiency in dwellings is an area that must be addressed.

There is also an increasing recognition that different approaches will be required to finally achieve near-zero-carbon housing. Different combinations of building fabric improvements, low carbon on-site generation and potentially additional payments to a central scheme to facilitate larger-scale low carbon systems being allowed to achieve effective emissions targets. This direction was outlined in the 'Allowable Solutions' proposal in the UK (ZCB, 2013), although this has also been scrapped as part of the recent re-evaluation of zero-carbon housing targets.

Noting that building legislation to-date has affected a relatively small number of UK new build and retrofit projects (compared to the total size of the housing stock), the net result of the rapid change in UK building regulations has been a gradual improvement in the energy performance of the housing stock as a whole; even in older buildings, energy efficiency levels are improving with increasing numbers of households installing fabric improvement measures such as double glazing, loft and cavity wall insulation (Palmer and Cooper, 2013). However, despite the various energy performance improvement drivers, overall energy use associated with the domestic sector has remained broadly static (DBEIS, 2016a) over the last 40 years, mainly due to socio-economic factors.

THERMAL ENERGY SUPPLIES

The vast bulk (80%) of the UK domestic sector's thermal energy (space heating and hot water) is from gas, with over 90% of dwellings in the UK connected (or with ready access) to the gas grid (DBEIS, 2016a). Other significant fuel sources include electricity, oil, and bioenergy, mainly for premises where has is unavailable. Figure 1 shows the different thermal energy fuel sources for UK dwellings as of 2015.

As is clear from Figure 1, the total amount of thermal energy provided by on-site renewable sources to dwellings is a small proportion of the total energy supply (approximately 27.0 TWh compared to a total supply of 388 TWh). However, the contribution has increased significantly from 15.3TWh in 2011, partly as a result of the Renewable Heat Incentive scheme introduced in 2014. The bulk of this was supplied in the form of heat from wood or other biomass, accounting from some 86% of the total (DUKES, 2016). Solar thermal supplied 0.6 TWh of heat and heat pumps another 3.7 TWh, however these latter two figures are for the whole built environment, not just the domestic sector.

Heat and Power Supply Technologies

Gas and Liquid Fuel Boilers

The last 20 years has seen a radical shift in the means by which domestic heating and hot water has been provided. Historically, hot water has been stored in a central insulated tank and then distributed to the hot water taps; the hot water tank being heated either by a boiler or electric immersion heater. However, this picture has changed radically with the appearance of combination boilers: these provide instantaneous hot water and have enabled householders to remove hot water storage tanks from their dwellings. The traditional non-condensing boiler feeding radiators and a hot water tank accounts for around 20% of existing boiler installations. However, more modern condensing and condensing-combination boilers now account for 15 and 39% of boiler installations, respectively (DBEIS, 2016a).

Solid Fuel

Around 550,000 tonnes of coal was used in the UK domestic sector in 2015, down from over 700,000 tonnes in 2010 (DBEIS, 2016a). This accounts for approximately 1% of total UK coal demand and coal is the main form of heating for just 2% of UK homes (Palmer and Cooper, 2013). Solid fossil fuel use has been declining since the early '70s with the rise of gas central heating.

Microgeneration

In addition to action to improve energy efficiency, the introduction of a feed-in-tariff (FIT) in 2010 for local, small-scale electrical generation has induced a step change in the take-up of domestic power generation technologies (often referred to collectively as 'microgeneration'). Whilst microgeneration is a supply-side technology, its effect is broadly the same as energy efficiency measures in that net grid power demand is reduced; though if microgeneration penetration is sufficiently high, power flow could even be reversed (e.g. Hudson and Heilscher, 2012).

The introduction of the UK FIT has seen installation of almost 6GW of small-scale generation capacity, with around 99% of installations (and over 81% of installed capacity) being solar photovoltaic panels on housing and other buildings (DBEIS, 2017b).

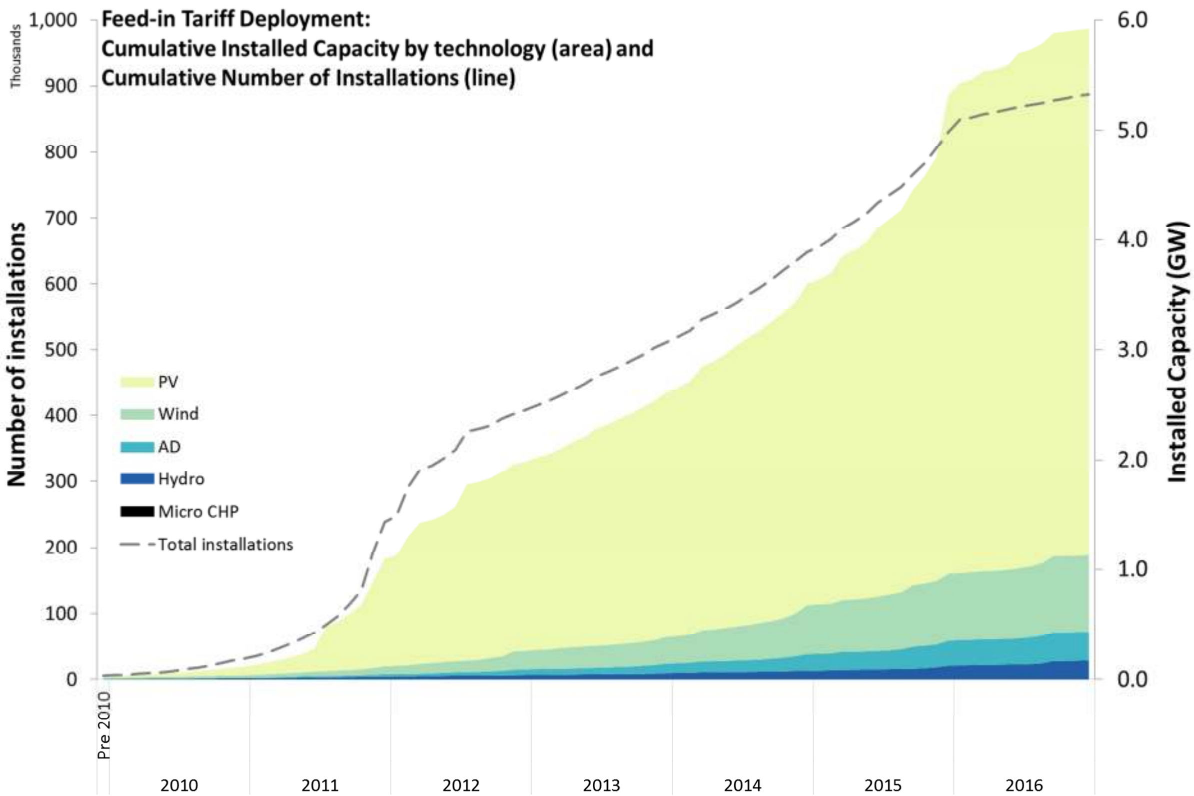

Figure 9: Cumulative feed-in tariff (FIT) installations since the launch of the FIT scheme (DBEIS, 2017b).

In 2014, the UK Government introduced the 'Renewable Heat Incentive' (RHI) (OFGEM, 2017c), which provides similar incentives to the FIT scheme for electricity for the small-scale generation of heat for energy efficient systems, such as heat pumps, biomass boilers, and solar thermal systems. As an example of the impact, domestic installations of biomass boilers and heat pumps increased by 44% in Scotland between 2014 and 2015 (EST, 2017a).

CHP

UK CHP capacity is some 5.6GW (DBEIS, 2017b), a reduction from 6.1GW in 2013, the majority of this being large scale large installations at industrial sites or large heat consumers such as hospitals. The occurrence of small scale CHP (<50kW) is significantly lower. Domestic Micro-CHP technologies are eligible for FIT (but not RHI) and there a number of technologies that have been on the market for several years that are gas powered, e.g. the Senertech-Dachs (5kWe) and the smaller Vaillant Ecopower (1kWe). These units provide power, space heating and hot water. However, due to the low cost of competing gas technologies such as boilers, their high cost, and requirement for additional thermal storage, the installation of micro-CHP into UK housing has been minimal as shown in Figure 9, with only 699 installations since the beginning of the FIT scheme; the majority of installations being around 1kWe in size.

PV

PV systems typically convert solar radiation to DC electricity, which is then inverted before being fed into the public electricity supply (typically connected at the consumer unit). If there is sufficient demand in a building, the PV generation will be absorbed within the building, however if demand is low the power produced by a PV installation will be exported to the local low voltage (LV) network. Since the advent of the FIT approximately 4.8 GW of domestic-scale PV has been installed in the UK (approximately 875,000 installations) (DBEIS, 2017b). The total PV capacity exceeds 10GW, with much of the larger-scale capacity installed under the Renewables Obligation. As the majority of UK housing uses gas for heating, the bulk of FIT PV installations do not contribute to heating demand. However, when installed in off-gas-grid housing, PV will make some contribution to offsetting heating carbon emissions and can be used to drive heat pumps. In the future, PV installations can also be integrated with domestic electric vehicle charging systems.

Wind Energy (SWECS)

The term small wind energy conversion systems (SWECS) covers a variety of wind turbine types from small rooftop mounted devices to larger stand-alone devices of 5kW and over.

The UK's installed wind capacity, exceeded 13 GW in 2016, with some 0.5 GW of small-scale wind installed under the feed-in-tariff (OFGEM, 2016a). Urban wind energy was largely discredited following the poor results from the Warwick wind trials (Encraft, 2009) and the vast majority of wind installations are in rural areas of the UK, for example in Scotland wind accounts for 36% of FIT installations compared to <1% in London (OFGEM, 2016a). The majority of rural wind installations are in buildings not connected to the gas grid, consequently these installations can make an appreciable contribution to space and water heating if integrated with heat pumps.

Direct Electric and Storage Heating

Approximately 2.2 million homes (8%) in the UK are reliant on electric heating. The bulk of these (1.7 million) use storage heating whilst the remainder utilise direct electric or heat pumps (OFGEM, 2015). The use of direct electric heating has increased recently with the installation of electrical only heating systems in flats, mainly for safety and economic reasons. Around 25% of flats use some form of electric heating system (Palmer and Cooper, 2013)

Heat Pumps

Heat pumps account for only 0.4% of all domestic and service sector heat demand (DBEIS, 2016c), with just over 140,000 installations by the end of 2015 and approximately 18-20,000 sales per year (Eurobserver, 2016). Both ground and air source heat pumps are subsidised under the RHI, however the high availability of gas supplies tends to limit the potential for installations, as currently heat pumps are not cost competitive with modern gas boilers (Hannon, 2015). The majority of heat pump installations are therefore to replace costly oil or solid fuel boilers or all-electric heating systems (Hannon, *ibid*).

The EST phase 1 field trial of 89 heat pump installations (EST, 2010) and phase 2 trial of 44 installations (EST, 2013) give a rough indication (although air source heat pumps are under represented) of the types of system seen in the UK, with the majority of installations being off-gas grid.

Air Source

Air source heat pumps (typically air-to-water) systems account for the vast bulk of UK heat pumps sales (Eurobserver, 2016), being cheaper to install and a ready replacement for existing gas boilers.

Typical in-situ coefficients of performance (COP) range from 2-3 over the course of a year as external air temperatures vary (EST (2010), Kelly and Cockroft (2011), EST (2013)). The typical size of an ASHP installation in UK housing us approximately 10kW, and approximately 13,400 applications for installation have been made since the introduction of the UK RHI (DBEIS, 2017a).

Ground Source

Due to high installation costs and high percentage of the population that live in urban areas, relatively few ground source heat pumps have been installed in the UK, with around 12% of annual sales being GSHP (Eurobserver, 2016). The typical size of a UK GSHP installation is around 13.5kW, with approximately 3,000 being installed since the introduction of the RHI (DBEIS, 2017a). Field trials have indicated that GSHPs have a marginally higher seasonal performance factor (SPF) than ASHP (2.82 as opposed to 2.45) (EST, 2013); however the difference in costs is substantial, with a GSHP installation costing approximately twice that of an equivalent ASHP installation (EST, 2017b).

Biomass

Biomass boilers cover a variety of different fuel types including logs, wood chip, wood pellet and biogas. All typically feed a domestic hot water heating system providing low temperature hot water. Since the introduction of the UK RHI in 2014 approximately 9,150 domestic biomass boiler systems applications have been made, accounting for approximately 32% of domestic applications (DBEIS, 2017a).

The average size of biomass installation is approximately 25kW (DBEIS, 2017a) indicating that installations would tend to be for larger properties. Biomass boilers are not a direct replacement for conventional gas boilers. Due to their greater thermal and slower response times these devices are not suited to intermittent operation, a thermal buffer tank being required to smooth out variations in demand and also to act as a heat dump in the case of the shutdown of the heating system.

Solar Thermal

A broad range of technologies could be classed as solar thermal, falling into two broad categories of active (i.e. incorporating some form of electromechanical system) and passive technologies. Of the active technologies, the most common in the UK housing sector are rooftop solar collectors, which are either the older flat plate type collector or more modern evacuated tube system. The most common passive solar technology is the conservatory, with 18% of homes in England reported to have a conservatory (BRE, 2013)

Active Solar Thermal

Up until the introduction of the UK feed-in-tariff solar thermal collectors were by far the most common form of domestic solar installation. However post-FIT, PV installations now dwarf solar thermal installations in the UK. Less than 3,300 solar thermal systems have been approved for installation under the RHI (DBEIS, 2017a) compared to almost 875,000 PV installations under FIT (DBEIS, 2017a). The total number of UK domestic solar thermal installations was around 110,000 in 2010, around 0.4% of the housing stock (BSRIA, 2014).

Passive Solar Thermal

The bulk of passive solar thermal installations in UK housing are conservatories, with approximately 5,000,000 installed UK-wide. Ironically, the majority of conservatories are used inefficiently, with gas or electric heating installed for year-round use resulting in increased heating costs (BRE, 2013). Ideally a conservatory should be unheated and only used during the summer and transition seasons, but this is rarely the case (BRE, 2013). Reliable data is not available for other domestic passive solar installations such as Trombe walls, however installation numbers are likely to be minimal.

Conclusions

This paper has set out the current state of domestic heat supply and demand in the UK, with the vast majority of heating needs currently met using the combustion of fossil fuels. This situation must change radically if the UK is to to meet the challenging carbon targets of an 80% reduction in greenhouse gas emissions by 2050 (HM Government, 2009) . The domestic sector in particular faces a range of challenges. Key issues are reducing the overall demand for heat and decarbonising the residual heat loads, which encompass both space heating and hot water provision. If the supply of electricity in the UK is progressively decarbonised at the macro and micro-scales, through the deployment of renewable generation, then the electrification of heat using heat pumps would be an effective means to provide the low-carbon space heat, hot water (and possibly cooling) required by the domestic sector. However, the widespread adoption of heat pumps would significantly increase the power flows on the electricity network. Wilson et al (2013) indicated that a shift of only 30% of domestic heating to heat pumps could result in an increase of 25% in the total UK electrical demand. To mitigate the potential negative impacts of heat pumps, particularly on peak demand and reduce or delay network upgrade costs, load shifting of household thermal demands could become essential.

Thermal storage would play a key role in facilitating both the integration of low-carbon heat sources and the electrification of heat. However, many obstacles exist with regards to integrating and operating heat storage systems in future buildings and communities, one of the most significant is competition for space - as dwelling sizes reduce , floor area is at a premium and the space penalty associated with conventional hot water storage acts as a barrier to its uptake; this problem becomes more acute if heat needs to be stored over longer time periods than is done at present. Storage in the future may need to migrate away from the traditional hot water tank at seen at present, towards media such as phase-change materials and storage that makes better use of the existing space and thermal mass in and around buildings, including large scale community storage. An attractive storage option is to integrate storage into the fabric of the dwelling – fabric integrated thermal stores (FITS). However, the effective operation of FITS, within the context of a low carbon future featuring multiple heterogeneous heat sources and active energy network participation raises significant engineering and social challenges. Some of these are as follows.

It is against this background that the EPSRC Fabric Integrated Thermal Storage in Low Carbon Dwellings project (FITS-LCD, http://fits-lcd.org.uk) is examining alternative approaches to the deployment of storage in housing. Specifically, the project looks at whether the intrinsic thermal mass in a building's fabric could be better utilised (either passively or actively) or modified to provide heat demand flexibility. The project is making use of both modelling and demonstration to explore the feasibility of fabric integrated concepts.

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