



Energy use intensities in London houses

RESEARCH

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ABSTRACT

This research compares domestic metered energy data, for both gas and electricity consumption, against characteristics drawn from a building stock model of Greater London, UK. The energy analyses are limited to houses (single-building, single household) with one standard electricity meter and one mains gas meter as the principal subset. This provides a sample of almost 1.2 million, or 75%, of London's stock of houses. Energy use was normalised by calculated floor area, providing an energy use intensity (EUI; kWh/m²/yr), which allows properties of all sizes to be compared. Examination of EUIs of each built form versus Energy Performance Certificate (EPC) current energy efficiency (Asset Rating value) indicates weak, or very weak, correlation between the two, particularly for electricity.

PRACTICE RELEVANCE

The study demonstrates how a detailed building stock model may be used for the analysis of metered energy use in the buildings of urban areas: in this case houses. The analyses examine some aspects of the data that constitute the stock model, such as built form and age, which are held at the scale of what can be considered to be individual buildings. The model currently covers Greater London, but is being built for other urban areas of England and Wales, thus giving it the potential to aid different layers of government or other actors in their efforts to reduce energy use in the building stock—both domestic and non-domestic. Some aspects of the model, such as the calculation of floor areas, should be replicable, where these data are accessible.

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KEYWORDS:

building stock; buildings; domestic; energy; Energy Performance Certificate; houses; residential; stock model; London

TO CITE THIS ARTICLE:

Liddiard, R., Godoy-Shimizu, D., Ruyssevelt, P., Steadman, P., Evans, S., Humphrey, D., & Azhari, R. (2021). Energy use intensities in London houses. *Buildings and Cities*, 2(1), pp. 336–353. DOI: <https://doi.org/10.5334/bc.79>

1. INTRODUCTION

In its efforts to contribute to the reduction of global emissions of greenhouse gases, with the aim of limiting global warming, climate change and their effects, the UK is legally committed to a target of net zero carbon emissions by 2050 (HM Government 2019). With the UK residential sector accounting for 77% of the 83 Mt of direct CO₂ emissions from the operation of UK buildings in 2017 (CCC 2018: 90), it is clear that this sector is a prime candidate for reducing the UK's energy use and consequent emissions.

The scope of the research presented here is currently limited to Greater London, which is the largest urban area in the UK and thus a significant user of energy. In addition to national government targets, the London Environment Strategy has set a target for London to become zero carbon by 2050 (Mayor of London 2018). An example of the implementation of policies to achieve these aims is the Minimum Energy Efficiency Standard (BEIS 2020) intended to improve building energy performance whilst also reducing fuel poverty. To meet such policy aims, it is first necessary to understand the current composition of the building stock, which consists of many individual buildings with a range of physical characteristics, including size. As building size is a prime determinant of gross delivered energy use, it is necessary to allow for this using normalisation by a standardised metric, such as building volume or floor area, to generate a comparable energy use intensity (EUI) applicable across combinations of other building characteristics.

Building stock energy demand models are often employed in the quest to understand the characteristics of building stocks and their energy use, as described by Steadman *et al.* (2020) Sousa *et al.* (2017) and Li *et al.* (2017), in particular. Methods frequently use archetypes based on samples, at various levels of detail, which are then apportioned to the wider stock (BEIS 2017, 2019; Cambridge Architectural Research 2012; Hulme *et al.* 2013; MHCLG 2016; UKSA 2020). In the UK, the English Housing Survey (EHS) (MHCLG 2020) is often used for this type of method.

Unlike the above sample-style strategies, Howard *et al.* (2012) developed an automated building stock model of New York, US, which was constrained by recorded energy use aggregated to the scale of a building lot, so each unit of analysis (the lot) could contain more than one activity, which reduces the utility of the model compared with one that can address energy use for each activity. However, that method also modelled energy end uses (heating, cooling, *etc.*). Elsewhere, Österbring *et al.* (2016) developed a geospatial building stock model, using an age-type archetype system for the City of Gothenburg, Sweden, validated against recorded energy data for 433 multifamily dwellings, but lacked access to energy data for single-household buildings. Other detailed models of limited geographical areas have also been produced, such as Jones *et al.* (2000), using 'on-the-ground' survey methods.

'Big data' approaches have been employed by Hartmann *et al.* (2016) to characterise the building stock of Germany, based on land use data coupled to building footprints, but residential uses were not differentiated into single- and multi-dwelling buildings and neither building height nor floor area were considered. Nishimwe & Reiter (2021) constructed a hybrid model of the building stock of Wallonia, Belgium, that assigns values for heat energy use to individual buildings, based on their floor area and an EUI for the building use type, derived from top-down statistics of energy use in buildings.

Unlike the work described above, the aim of the present research is not to model energy use but to use building characteristics held in a building stock model to analyse the recorded annual gas and electricity consumption of individual houses in a large urban area. Specifically, a 'house' is defined as a single-address dwelling that is considered to be a self-contained building, not part of a multi-dwelling building (*i.e.* not an apartment block, or part thereof; and not sharing a building with non-domestic activities). In particular, the research focuses on houses that are most likely heated using grid-supplied natural gas. 'Energy epidemiology' (Hamilton *et al.* 2013) is used to generate EUIs with annual energy use normalised by floor

area as units of kWh/m²/yr, enabling the energy performance of houses of different sizes to be compared. This method of assessment is not often employed for domestic properties due to a lack of floor area data, but it is particularly useful for stock models that encompass both domestic and non-domestic activities, as the latter are generally assessed in units of EUI to allow the direct comparison of buildings, or premises, regardless of size. The calculated EUIs are used to examine energy use and how this relates to house characteristics and statutory building asset rating schemes.

This article briefly describes the primary data inputs to a building stock model and how these are collated, plus the addition of recorded energy data and building asset ratings required by the Energy Performance of Buildings Directive (European Parliament & Council of Europe 2002), followed by the cleaning processes applied. Delivered energy data for gas and electricity are coupled to floor areas to create EUIs, which are then analysed by attached status (built form) and age. Next, the relationship between asset ratings and actual EUI is investigated. Finally, the implications of the findings are considered.

2. DATA AND MODEL CONSTRUCTION

The 3DStock building stock model of Greater London (Evans *et al.* 2016, 2017) automatically collates the following datasets to generate a bottom-up, disaggregate, geometrical, geospatial building stock model that captures both domestic (residential) properties and non-domestic premises, including where these are mixed in the same building(s). The primary datasets are:

- Ordnance Survey AddressBase Premium (OSAB)
 - Inputs: geolocated addresses or Unique Property Reference Numbers (UPRNs) identifying domestic and non-domestic address points
- Ordnance Survey Master Map Topography Layer (including simple building height and sites layer)
 - Inputs: building footprints and simplified heights (where LiDAR fails—see below); site boundaries
- Her Majesty's Land Registry INSPIRE Index Polygons
 - Inputs: property land boundaries
- Valuation Office Agency (VOA) Non-domestic Rating Data
 - Inputs: addresses, activities and floor areas for most non-domestic premises
- UK Environment Agency Light Detection and Ranging (LiDAR) data
 - Inputs: geolocated, high-resolution height data for buildings

The above shows that *per se*, 3DStock is not an energy use model, but a base onto which energy-related (or other) data may be layered. A schematic of the data linkages is provided in Appendix A in the online supplemental data. The 2017 iteration of the model, used here, accounts for more than 98% of the 1,578,800 houses in the London government region (VOA 2015). In addition to the above data inputs, information on the approximate construction date of buildings comes from a proprietary dataset called UKBuildings, supplied by the GeoInformation Group (see Acknowledgements). This information is joined to the model spatially. 3DStock is currently being expanded to include more of the urban areas of England and Wales.

2.1 CLASSIFICATION OF 'HOUSES', INITIAL COUNTS AND FILTERING

The work presented here is for houses consisting of a single map footprint and a single domestic address only (no subdivisions). Outbuildings that may be associated with the house are typically unheated, so these are excluded.

Table 1 shows the counts of houses in the 3DStock model of Greater London, subdivided by attached status, classified as: detached (generally four major external walls); semi-detached (generally three major external walls, plus one shared); end-terrace (generally three major external walls, plus one shared); and mid-terrace (generally two major external walls, plus two shared). The top row of data gives the total number of houses, with each subsequent row describing incremental data cleaning, because the scale and complexity of 3DStock results in a small proportion of the model containing unlikely data or internal inconsistencies, such as implausible areas and volumes. As errors and omissions in input data (e.g. some of the LiDAR data are missing), or uncertainties occur in the modelling process, dimensional filters have been applied to the houses in filters A and C. Note that the attached status is determined automatically by the model.

2.2 ENERGY DATA AND ENERGY PERFORMANCE CERTIFICATES (EPCS)

Energy use data were provided to the researchers by the UK Department for Business, Energy and Industrial Strategy (BEIS), under a data sharing agreement, with strict privacy conditions applied. Annualised and weather-corrected energy use in kilowatt hours (kWh) per year was supplied for gas consumption meters (meter point reference numbers—MPRNs), together with annualised consumption in kWh for electricity meters (meter point administration numbers—MPANs). Note that these data are not just those matched in the National Energy Efficiency Data-framework (NEED) (BEIS 2013) and have been provided in a raw state. The data for 2016 were attached to 3DStock using automated address-matching algorithms.

Following the address-matching process, if an MPAN had multiple records, all records for that MPAN were removed. There were no repetitions of MPRNs. The remaining MPANs and MPRNs were matched to each house's UPRN in OSAB, based on textual address-matching. The MPAN data include the 'profile class' (PC) (ELEXON 2018) of the electricity meter and the recorded annual delivered energy in kWh. In filter D of **Table 1**, all PC '1' (unrestricted domestic consumption) and PC '2' (Economy 7-type, off-peak) meters were included. For filter E, all MPANs required consumption > 0 kWh and in filter G all MPRNs had consumption > 11 kWh, as this is approximately the energy content of the smallest volume of gas measurable by a mains meter. The one-to-one meter relationship in filter H overcomes the possibility that a house may have an MPAN matched to it, but the matching of the appropriate MPRN has not been achieved. This filter also excludes profile class '2' MPANs, as these ought to be more likely to be associated with electric heating (ELEXON 2018), though the data suggest that this is not necessarily the case (requiring further research). Note that apart from the profile classes for electricity meters, the energy data contain little or no information about what is on the downstream side of the meter, such as whether the consumer is residential, such as a house, or the nature of energy consuming equipment etc.; hence, the need to link the data to a model of buildings and their characteristics.

Energy Performance Certificates (EPCs) are the UK's Asset Rating tool as originally required by the Energy Performance of Buildings Directive (European Parliament & Council of Europe 2002). The EPC models energy performance using the Standard Assessment Procedure (SAP), giving a rating score of 1–100, where 100 is the most energy efficient (BRE 2014). For many older buildings, Reduced Data SAP (RdSAP) is used, requiring fewer construction details but relying on more in-built assumptions about the relationships between characteristics, e.g. wall *U*-values based on the period of construction (BRE 2019). EPCs were designed principally as a means for householders to gauge the costs resulting from the theoretical standardised provision of heating, hot water and lighting (the major fixed energy use systems in homes) in a property, in the hope/expectation that this would drive down energy use. EPCs have been in use since 2008 and are now being used in UK government policies (BEIS 2018), such as the Minimum Energy Efficiency Standard (BEIS 2020) to reduce energy use in the building stock. A sound appreciation of the utility of EPCs is thus fundamental to their future role in energy conservation.

When used in large numbers and cross-referenced to datasets with broader scope (in this instance, 3DStock), EPCs can be used to provide a description of buildings for use in the evaluation of how buildings might be changed and what the effects might be on energy use. Since the bulk release

of EPCs and some of their underlying data by the Ministry for Housing, Communities & Local Government (MHCLG) (2017a, 2017b), research has identified considerable uncertainty around the accuracy of ratings and how representative they are of actual energy use (Crawley *et al.* 2019; Jenkins *et al.* 2017; Summerfield *et al.* 2019). These works are important because EPCs are seen by government as a key descriptor of the whole building stock and are used as a means of predicting changes in energy use resulting from the upgrading of building energy performance. The work here compares recorded energy use with EPC performance ratings, subdivided by building age and attached status.

The bulk release EPC data were automatically address matched to UPRNs in 3DStock. In the EPC register, properties can have multiple EPCs, though only the most recent was current at the time of the data release. Because the register includes certificates lodged after the target date of this research (April 2017), it was necessary to use only the certificate closest to, but not later than, the target date. Within the remaining certificates there are still implausible data, such as an SAP rating > 100, or floor area < 6m², so filters I and J in **Table 1** were applied to remove these. The final row of **Table 1** shows that after these cleaning processes, the sample contains 462,355 records, or 29.8%, of houses in the model. Data for each house include: attached status; construction age band; estimated gross external floor area (m²); annual gas consumption (kWh); annual grid-supplied electricity consumption (kWh); presence of an EPC; current energy efficiency (SAP rating) and grade, where present; and geographical location.

Table 1 Counts of houses, per attached status, at each level of cumulative data filtering.

Notes: ^aHouse estimated floor area is gross external area, so the threshold is increased to allow for the gross internal area of the EPC ‘inside’ the walls of the house.

^bPC = profile class; see the text.

^c11 kWh is the equivalent of about 1m³ of gas, the smallest volume of gas measurable by a gas meter.

FILTER CODE	APPLIED TO	FILTER CRITERIA	DETACHED (n)	SEMI-DETACHED (n)	END-TERRACE (n)	MID-TERRACE (n)	SUM (n)
		All houses with an attached status	193,302	373,893	282,513	700,261	1,549,969
A	3DStock	With a building volume > 12 m ³ and trusted; footprint > 6 m ² ; estimated floor area > 6 and < 1100 m ² ^[a]	172,725	347,845	265,672	666,816	1,453,058
B	3DStock	With age band	167,195	345,388	261,820	656,936	1,431,339
C	3DStock	With floor count > 0 < 7 and not null	167,146	345,282	261,718	656,374	1,430,520
D	Electricity	With matched PC1/PC2 MPAN(s) ^b	160,617	339,585	256,548	644,871	1,401,621
E	Electricity	With PC1/PC2 MPAN(s) ^b and annual consumption > 0 kWh	159,873	337,795	254,707	639,902	1,392,277
F	Gas	With MPRN(s)	156,055	333,321	248,508	622,284	1,360,168
G	Gas	With MPRN(s) and annual kWh > 11 ^c	154,304	329,595	245,295	614,328	1,343,522
H	Gas and electricity	With 1 MPRN and 1 PC1 meter ^b	132,042	289,853	218,413	553,407	1,193,715
I	EPCs	With a matched and valid EPC	44,831	101,125	87,893	235,616	469,465
J	EPCs	With EPC total area > 6 and < 1000 m ²	44,054	99,460	86,551	232,290	462,355
		Filter J as percentage of all houses with an attached status	22.8%	26.6%	30.6%	33.2%	29.8%

3. RESULTS AND DISCUSSION

As a preliminary analysis, the distributions of floor areas for each attached status and age band are displayed in **Figure 1**, for filter H (in **Table 1**). The overall median floor area of detached houses in Greater London is approximately one-third larger than mid- and end-terrace houses, with semi-detached being about 8% larger than mid-terrace houses. The interquartile ranges are limited, with only detached showing much variation. Interestingly, semi-detached and terraced houses seem to have increased in size in recent years, though these represent a small proportion of the stock.

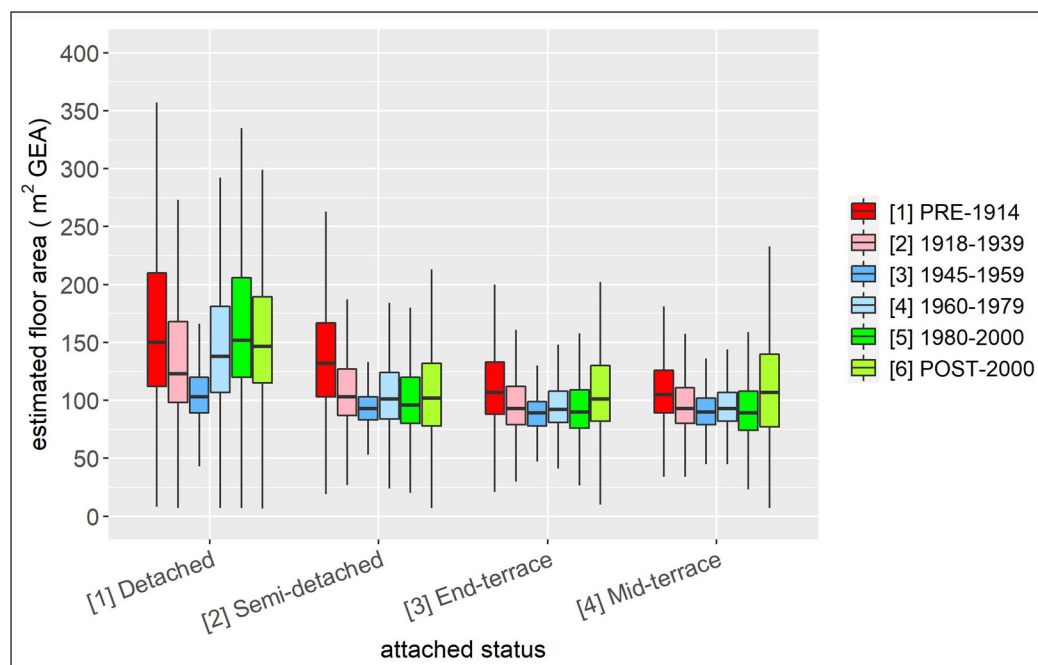


Figure 1: Estimated floor area (m² gross external area) per attached status (see filter H in Table 1).

3.1 TOTAL DELIVERED ENERGY USE INTENSITY

EUIs (kWh/m²/yr) for total delivered energy use were generated using the floor areas calculated from the geometry of each building within the 3DStock model. As these areas have not been measured onsite, they are deemed to be estimates, though the calculation process is automated and standardised as a gross external area. This is shown in Table 2. Filter H, from Table 1, identified unfeasible maximum values, so to remove outliers an upper threshold for total delivered EUI was applied, using modified Z-scores (Iglewicz & Hoaglin 1993; NIST/SEMATECH 2012). The result, in the lower part of Table 2, indicates a minimal effect on the medians and means, though the coefficient of variance (CoV) does change, indicating the compression of the ranges.

Table 2 Summary statistics of the total delivered energy-use intensity (EUI; kWh/m²/yr), using estimated floor area, for each attachment status, with and without the application of the upper EUI threshold.

Note: CoV = coefficient of variation; SD = standard deviation.

ATTACHED STATUS	COUNT	MINIMUM	25TH PERCENTILE	MEDIAN	75TH PERCENTILE	MAXIMUM	MEAN	SD	CoV
<i>Filter H (with one gas meter and one profile class 1 electricity meter)</i>									
[1] Detached	132,042	0	151	198	255	9,386	212	116	0.547
[2] Semi-detached	289,853	0	157	203	258	3,649	215	94	0.437
[3] End-terrace	218,413	0	149	197	254	32,805	211	132	0.626
[4] Mid-terrace	553,407	0	132	176	226	8,704	185	87	0.470
All	1,193,715	0	143	188	242	32,805	200	102	0.510
<i>Filter H and total delivered estimated EUI (kWh/m²/yr) outliers removed (see the text)</i>									
[1] Detached	131,409	0	151	198	254	592	208	86	0.413
[2] Semi-detached	288,516	0	156	203	257	588	212	85	0.396
[3] End-terrace	217,182	0	149	196	253	595	207	87	0.420
[4] Mid-terrace	551,123	0	132	175	225	531	183	78	0.421
All	1,188,230	0	142	188	242	595	187	83	0.421

3.2 DELIVERED GAS ENERGY USE INTENSITY

Figure 2 shows the distributions of gas EUI based on the model's estimated floor areas for each combination of attached status and age band, using the houses in the lower part of **Table 2**. For each attached status there is a general decline in gas consumption moving from older to more recent age bands, which follows the expected trend for heating energy use to reduce with improvements in construction technologies and methods. However, in each attached status, houses built in the period 1918–39 have higher median gas consumption than in the succeeding and *preceding* periods. Also going against the general trend, the semi-detached, end-terrace and mid-terrace houses of the post-2000 period also have higher gas consumption than those built in the period 1980–2000. Ignoring age, little difference is observed between detached and semi-detached houses (median EUI = 162 and 164, respectively), but gas use intensity declines in end-terrace and mid-terrace houses (EUI = 157 and 138, respectively). This is expected, as the reduced exposed surface area resulting from mid-terrace buildings having two party walls causes less heat to be lost to the external environment. Semi-detached houses have marginally higher median gas EUIs compared with detached houses, which may seem counterintuitive due to the existence of party walls in the former. However, detached houses are generally larger (**Figure 1**), which has the effect of reducing the surface-to-volume ratio, lowering heat loss for a comparable floor area. This is confirmed for the sample by a calculation of the median compactness ratio (exposed surface area/volume) for each attached status: detached = 0.648; semi-detached = 0.609; end-terrace = 0.615; and mid-terrace = 0.45.

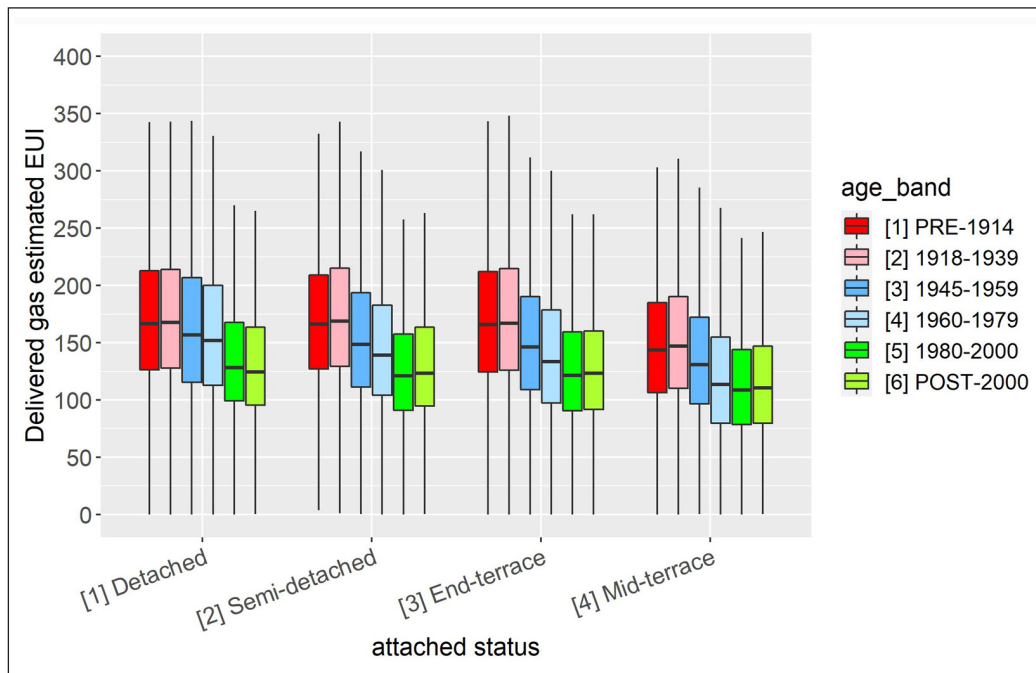


Figure 2: Delivered gas estimated energy use intensity (EUI; kWh/m²/yr) per attached status and age band.

Gas EUI for each attached status does not follow a normal distribution (see Appendix B in the supplemental data online). Although the four house types are largely similar in their distributions of EUI (**Figure 2**), using a Kruskal–Wallis test (*The concise encyclopedia of statistics* 2008) and subsequent Dunn test (Dinno 2015) returns a $p < 0.05$ for each pairing of attached status, indicating that each is a separate population. In particular, results suggest that end-terrace houses should be considered separately to the mid-terrace houses that form part of the same terrace *and* considered separately to semi-detached houses. The same tests applied to each age band indicates that these too are separate populations (all $p < 0.05$).

Figure 3 demonstrates very little variation in electricity EUI between the house types. The pattern of median electricity use is similar within each attached status with the highest EUI in the 1945–59 age band. However, setting aside age, detached houses have the lowest median EUI (detached = 32, semi-detached = 35, end-terrace = 36, mid-terrace = 34), which may be a function of these houses being generally larger, leading to a lower density of electrical appliances per unit area, e.g. one refrigerator per house regardless of the size of the house. The minimal spread of EUI across the attached statuses indicates that built form is not a key driver of electricity consumption. Again, the electricity EUI data of each attached status are not distributed normally (see Appendix B in the supplemental data online).

The Kruskal–Wallis (*The concise encyclopedia of statistics* 2008) and Dunn's tests (Dinno 2015) identify separate populations within the overall, but also indicate that post-2000 houses are from the same population as pre-1914 houses ($p = 0.49648$) and 1960–79 houses ($p = 0.18239$), which suggests other non-age-related factors are having an effect. When the tests are applied to attached status, each is a separate population (all $p < 0.05$). Although less diverse in terms of median EUI than gas use, electricity EUI appears to be at least partially governed by building age and built form.

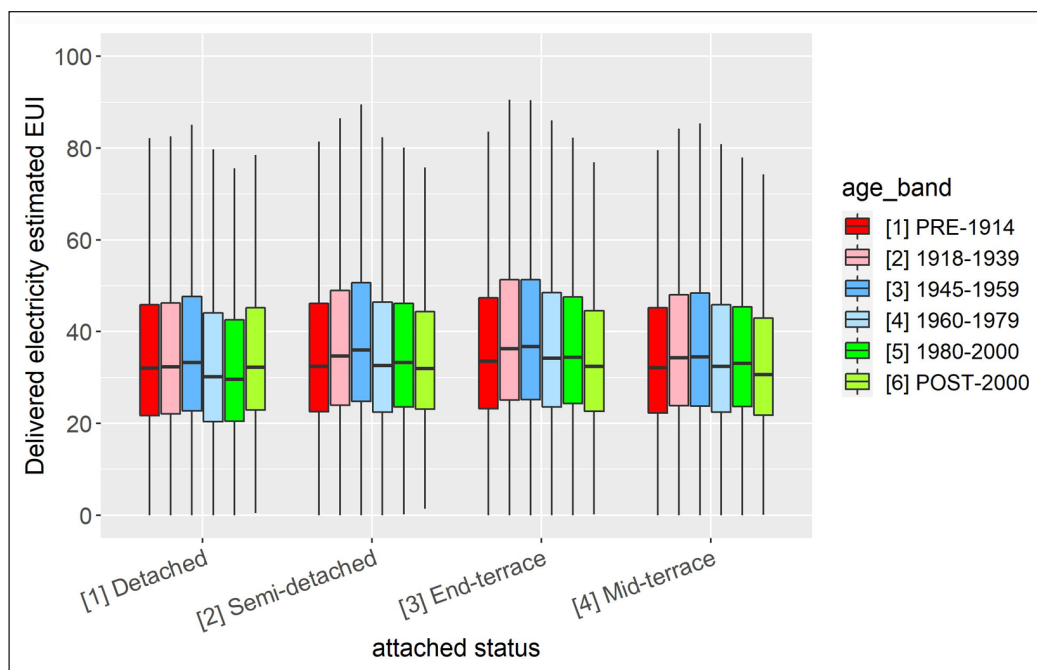


Figure 3: Delivered electricity estimated energy use intensity (EUI; kWh/m²/yr) per attached status and age band.

Median electricity use is lower in the post-2000 age band compared with the 1980–2000 band, whilst **Figure 2** shows higher median gas consumption in the newest age band compared with the preceding age band. Combining this with the increased median floor areas of **Figure 1** suggests that absolute delivered gas consumption increases in newer semi-detached and terraced houses, whilst electricity use is reduced. The opposite is the case for detached houses where electricity use has increased, whilst gas EUI and floor areas have decreased. Higher electrical EUIs might be assumed to increase internal heat gains, but testing for correlation between gas EUI and electricity EUI produces a Spearman's $r = 0.3231$ across the whole sample ($n = 1,188,230$). This suggests that the two EUIs are only weakly correlated and that the phenomenon of lower gas EUIs, or higher electricity EUIs (depending upon the direction of observation), may be driven by other building physics-related or occupant behavioural characteristics. This requires further investigation, initially of building characteristics data common to the properties with and without EPCs, i.e. not the data held in the EPCs. Obtaining occupier characteristics for such a large sample is currently beyond the scope of the work, but alignment with smaller, more detailed occupant studies may prove valuable.

3.4 GAS AND ELECTRICITY EUIS USING EPC FLOOR AREAS

Using floor areas from EPCs allows the generation of EUIs according to these recorded data. Medians for delivered gas EUIs are shown in [Figure 4](#), demonstrating that gas consumption is highest in properties of the 1918–39 age band, for each attached status, despite it being reasonable to expect lower levels of heating energy use than the earlier pre-1914 age band, resulting from improved construction methods, such as cavity walls. Apart from the interwar (1918–39) age band indicating high gas consumption, there is a general decline across the subsequent age bands.

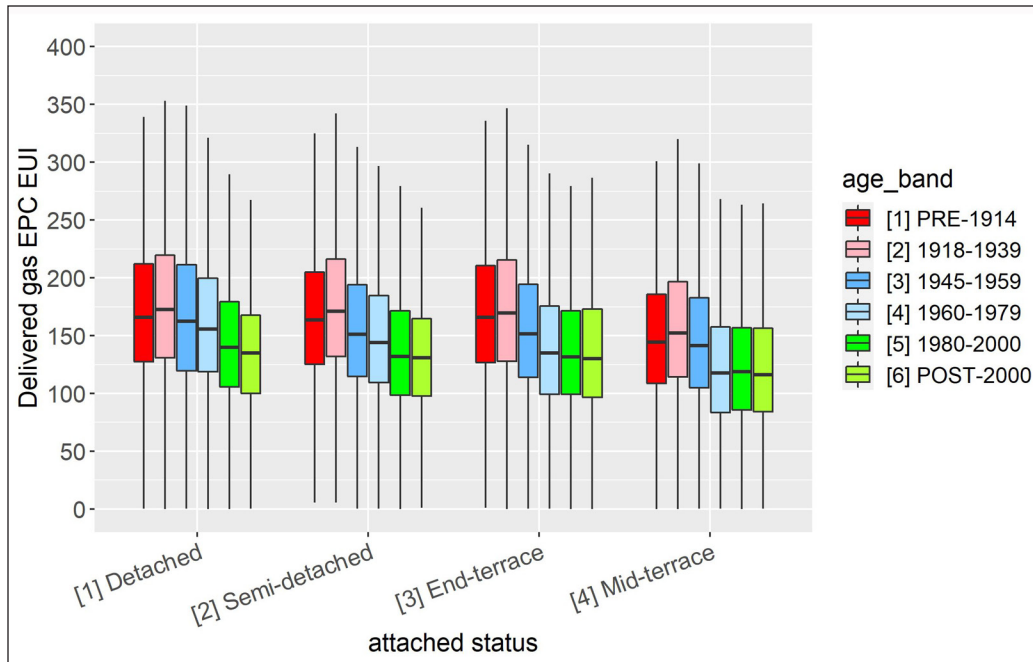


Figure 4: Delivered gas energy use intensity (EUI; kWh/m²/yr), based on Energy Performance Certificate (EPC) floor areas, per age band and attached status.

Unlike gas use for each attached status, median electricity consumption is highest in the post-war (1945–59) age band ([Figure 5](#)). Lower EUIs for the pre-1914 period compared with the following period are still evident and overall there is a minimal decline in electricity use moving from the oldest to newest properties. Comparison with [Figure 4](#) indicates that electricity consumption is not related to age and built form in the same manner as gas consumption.

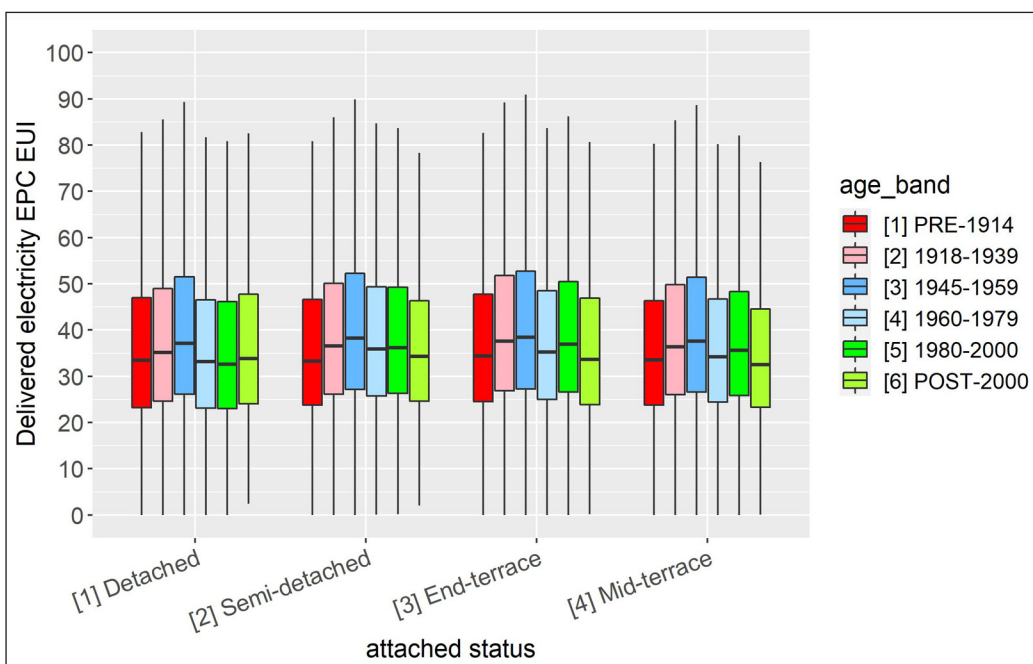


Figure 5: Delivered electricity energy use intensity (EUI; kWh/m²/yr), based on Energy Performance Certificate (EPC) floor areas, per age band and attached status.

4. EPC CURRENT ENERGY EFFICIENCY RATING

The current energy efficiency (SAP rating) data within EPCs were examined. **Figure 6** shows the median energy efficiency, per attachment status, across all age bands. There is a trend for scores to improve (increase) moving from older to newer properties, which is to be expected as construction techniques, materials and standards (should) have improved over time. The 1960–79 age band demonstrates some divergence away from this trend, however, in detached houses. Quite why this divergence occurs is not yet fully understood, but it may be due to errors in allocation to this age band, which might contradict the actual building age, and thus the assumptions inherent in the calculation of the relevant EPC, which should be based on close observation and dating by the assessor.

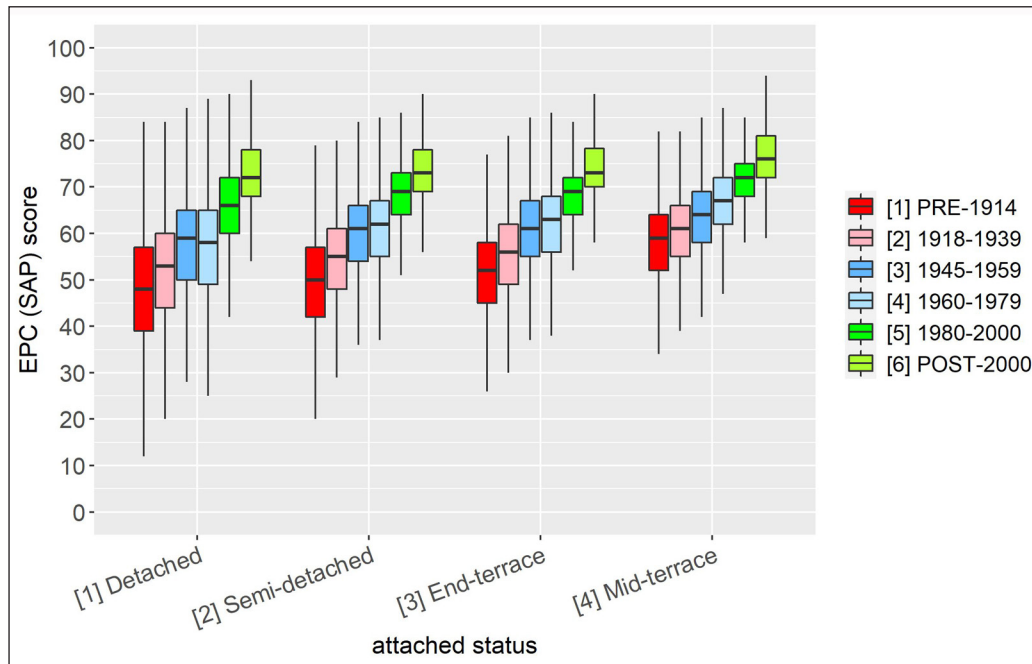


Figure 6: Energy Performance Certificate (EPC) current energy efficiency (Standard Assessment Procedure (SAP) rating), per age band and attached status.

In conjunction with the above analysis of gas EUI (**Figure 4**), examination of EPC current energy efficiency (SAP rating) suggests that houses built in the period 1918–39 are performing badly compared with their SAP rating, assuming all source data inputs and subsequent outputs are correct. Quite why this age band should be performing below the level suggested by EPCs is uncertain, but it might be a function of the transition from solid brick walls to cavity walls. Although cavity walls are generally considered to conduct less heat and be easily filled with insulation, perhaps early walls of this type were of poor quality, resulting in an inability to retrofit cavity wall insulation. Another possibility is that local London bylaws required the continued use of solid brick wall structures during at least the early part of this period (Pickles 2016). This hypothesis gains credibility as **Figure 7** shows that of houses built between 1939 and 1945 and having an EPC, three-quarters do indeed have solid brick walls (as recorded in the EPC). However, the EUI analysis suggests that these interwar solid wall houses have an actual performance worse than earlier types, despite having a nominally similar wall construction. This may be due to other factors of construction techniques and architectural fashion, such as an increase in the use of materials with poor insulation characteristics and/or more complex building shapes resulting in larger exposed surfaces and higher heat losses.

The data show that the rate of construction during this interwar period was extremely high (**Figure 8**), which may have had detrimental effects on quality (e.g. high infiltration rates), affecting thermal performance. As this age band contains only houses built long before the introduction of EPCs, they are likely to have been assessed using RdSAP, which employs more assumptions than SAP. Errors in RdSAP assumptions of the thermal resistance of walls (solid brick = $2.1 \text{ Wm}^2\text{K}$; cavity wall = $1.6 \text{ Wm}^2\text{K}$; BRE 2019, 131, tab. S6) constructed during this period, or mistakes in

correctly identifying wall type, may be the case. The former seems likely, as all attached statuses are affected by the phenomenon. The RdSAP assumptions about wall thermal performance could be tested through modelling, but misidentification of wall type, or age, is more difficult to confirm without visual inspection or access to other relevant (high-quality) datasets. Another scenario is that the EUI may be influenced by the heating systems or characteristics of the households in these properties, such as higher levels of income allowing increased energy use without having a severe impact on affluence. Again, the system type may be analysed, but occupant data remain inaccessible.

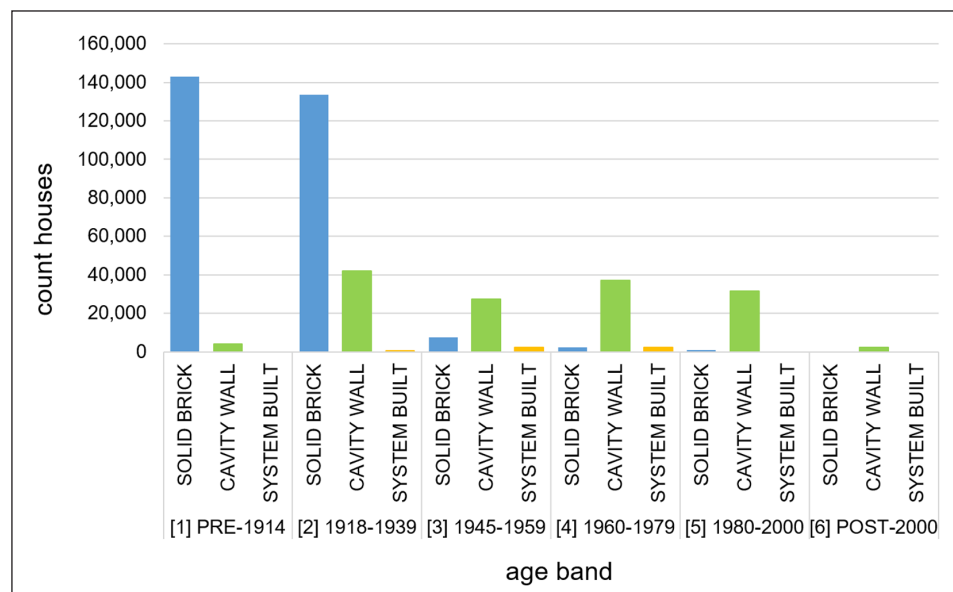


Figure 7: Counts of houses with Energy Performance Certificates (EPCs), per age band and major wall type.

The existence, or not, of basements may also be affecting gas energy use in these inter-war properties. The English Housing Survey (EHS) of 2008 states:

The majority (75%) of dwellings with basements were houses. Most of these houses with basements were owner occupied (85%) and two thirds (67%) were built before 1919.

(MHCLG 2013: 11)

If this is also valid for London’s stock of houses, it might result in apparently lower EUIs for properties with a basement, due to reduced heat losses through the walls of basements, the floor areas of which should be included in the EPC floor area (if they are deemed to be occupied). If these houses are also predominantly owner-occupied (as suggested by the EHS), this could indicate higher household incomes and thus perhaps less concern about the cost of energy as a proportion of household income.

The urban heat island (UHI) phenomenon may be having an effect, as houses built in the interwar period were largely part of the rapid expansion of London to form the suburbs of Outer London. These districts have lower spatial densities, as described by Smith & Crooks (2010) and Evans *et al.* (2018), which are likely to reduce the UHI effect compared with Inner London where earlier houses are more prevalent, thus theoretically a slight increase in gas consumption is required for heating in the suburbs containing interwar houses. **Figure 8** shows a summary of the age of houses located in Inner and Outer London, demonstrating that the bulk of 1918–39 houses are located in Outer London where the UHI is less pronounced, as described by Mavrogiani *et al.* (2009).

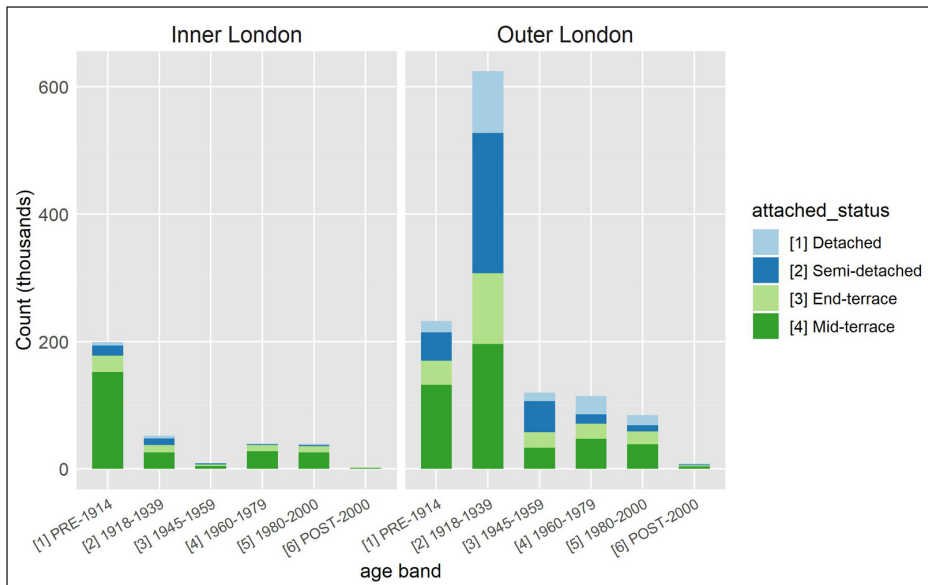


Figure 8: Counts of houses, per age band and attached status, in Inner and Outer London.

4.1 GAS AND ELECTRICITY EUIS VERSUS EPC CURRENT ENERGY EFFICIENCY (SAP RATING)

The last of these analyses looked for a relationship between gas and electricity consumption versus EPC current energy efficiency (SAP rating). As the EUIs are not normally distributed, Spearman’s non-parametric ranked order test of correlation was used. For gas consumption, Spearman’s r -values indicate a weak, negative correlation between gas EUI and the EPC current energy efficiency score for detached ($r_s = -0.225$) and end-terrace ($r_s = -0.194$) houses. Semi-detached and mid-terrace houses show a very weak negative correlation ($r_s = -0.154$; $r_s = -0.156$, respectively). For visualisation, density scatter plots are provided in **Figure 9**, where the gas use intensity (‘delivered gas EPC EUI’, on the y-axis) employs the floor area recorded in EPCs. Note that the density scales change according to the number of records being analysed and that the yellow hexes each contain $< 0.01\%$ of the total in each chart. The count (n) and Spearman’s r correlations are performed on the entirety of the input data, not just those within the grey scale of counts. The same applies to **Figure 11**.

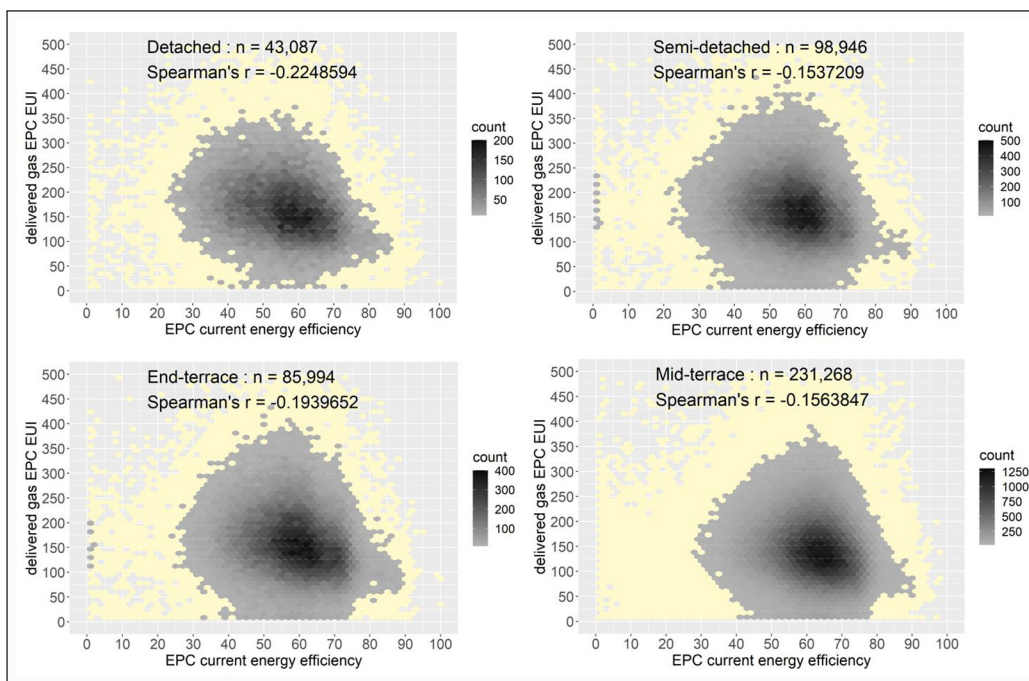


Figure 9: Scatter density plot of delivered gas energy use intensity (EUI; kWh/m²/yr, using areas from Energy Performance Certificates—EPCs) versus EPC current energy efficiency for each attached status.

The distributions of gas EUI are also shown in **Figure 10**, grouped by EPC grade, age band and attached status. EPC current energy efficiency is expressed here in bands A–G, with band A predicting the best performance, as shown on certificates. Note that for **Figure 10** EPC grades A and B have been amalgamated to retain data privacy. The trends, in both age and attached status, clearly indicate increasing EUI as EPC performance degrades, but EUI decreases in grade G. As the EPC grade deteriorates, tracking the medians, the interquartile range also shifts higher, except for grade G. This is likely due to under-heating of G-grade homes with poor energy performance. Reading across the medians confirms that houses constructed between 1918 and 1939 have the highest median EUI when compared with equivalent EPC grades in all other age bands. The best performing (A or B) houses account for only 1.1% of the 460,000 sample houses, whilst the grade C houses account for 15.9%, D for 49.8%, E for 27.6%, F for 4.7% and G for < 1% (percentages rounded).

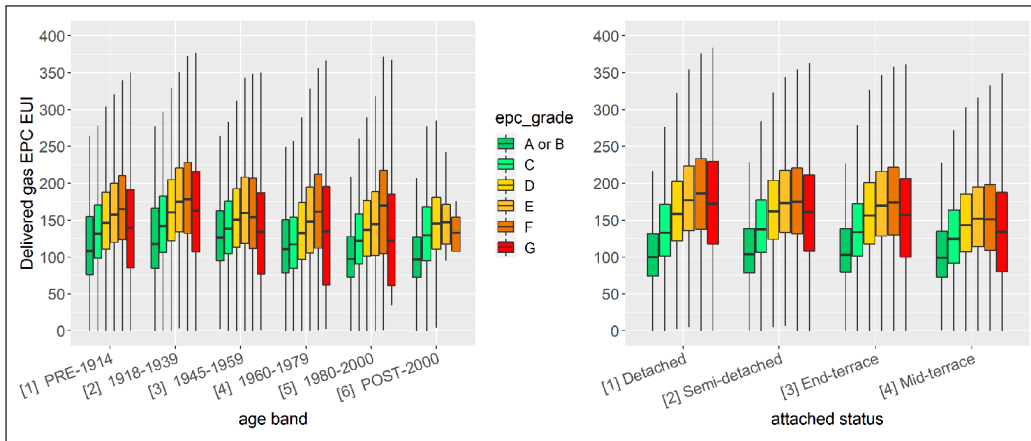


Figure 10: Distributions of delivered gas energy use intensity (EUI; kWh/m²/yr, using areas from Energy Performance Certificates—EPCs) versus EPC grade for each age band (left) and attached status (right).

Figure 11 shows electricity use intensity versus EPC current energy efficiency, using the same area metric and statistical methods, which produces Spearman’s r (< 0.05) giving no correlation between the axes. This indicates that EPC current energy efficiency is not a robust indicator of actual delivered electricity use for houses in Greater London and perhaps the wider UK stock. This is to be expected, as electrical plug loads are excluded from the SAP method, so it is heavily biased towards regulated loads, which are unlikely to be significant for electrical energy use in this sample of houses with gas supplies and no profile class 2 electricity meters. Also, lower levels of electricity EUI, coupled to a reduced variability, suggest that there are constraints on just how much appliance electricity use might be reduced in future. This suggests a greater emphasis could be placed on the decarbonisation of energy, in particular space heating, the need for which is currently met by gas in the bulk of the UK domestic building stock.

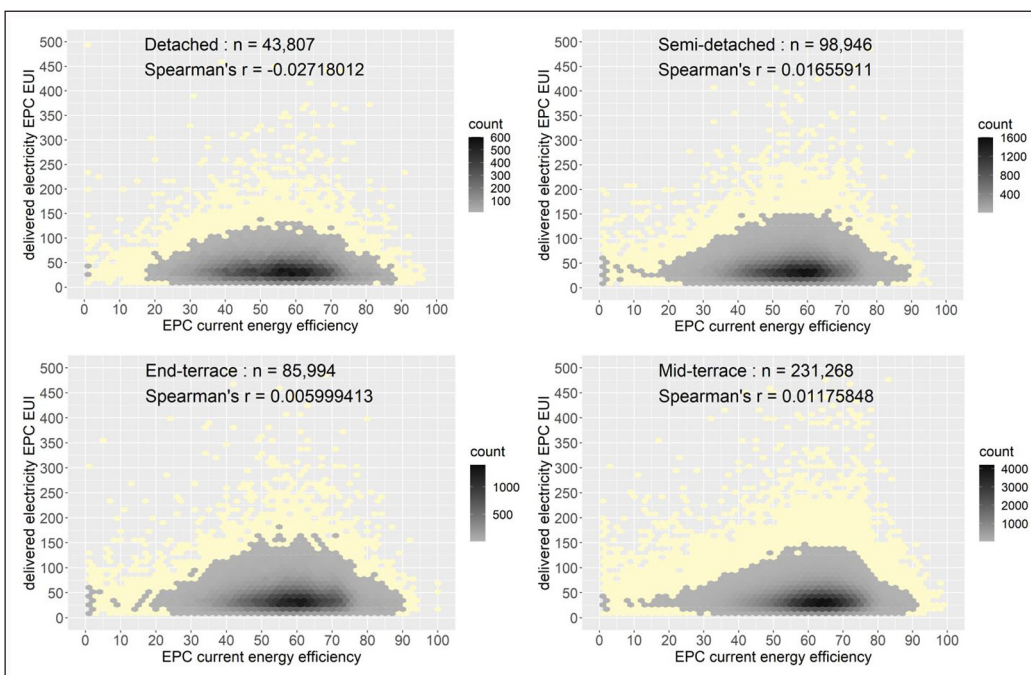


Figure 11: Scatter density plot of delivered electricity energy use intensity (EUI; kWh/m²/yr, using areas from Energy Performance Certificates—EPCs) versus EPC current energy efficiency for each attached status.

Distributions of electricity EUI based on EPC floor areas are provided in **Figure 12** for combinations of EPC grade, attached status and age band. This does not demonstrate the very distinct pattern of increasing EUI as EPC rating degrades, with little variation in the median or the interquartile range; indeed, there is almost no variation in median EUI in the pre-1914 age band, regardless of EPC grade. In all age bands, except the most recent, the performance of grades D and E houses is very similar and, as noted previously, these bands account for more than three-quarters of the sample. Within the groups of detached, semi-detached and end-terrace houses, there is a slight trend of declining electricity EUI as EPC grades deteriorate from D to F. In these two analyses of electricity EUI, the grade A or B houses perform consistently the best; however, 73% of these were built after 1979, reflecting low rates of construction (**Figure 8**) but with more stringent energy performance regulations for fixed lighting and the heating of domestic hot water, which ought to be reducing the electrical EUI.

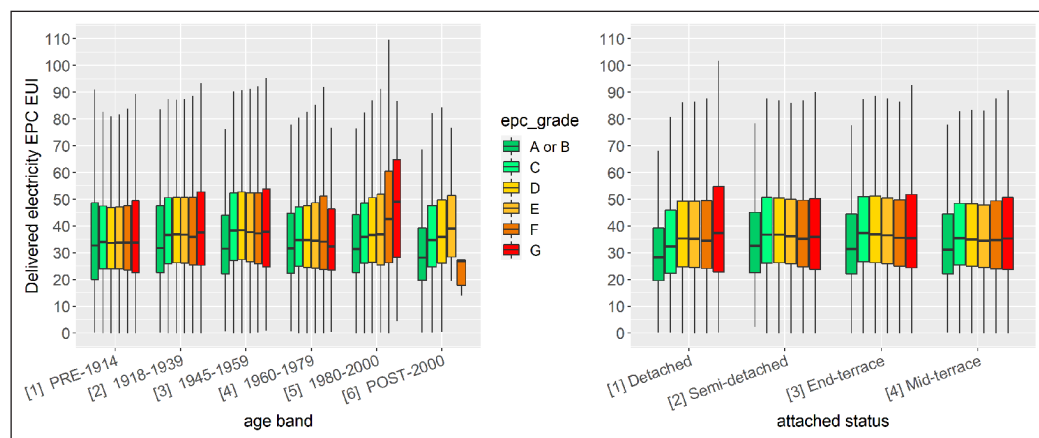


Figure 12: Distributions of delivered electricity energy use intensity (EUI; kWh/m²/yr, using areas from Energy Performance Certificates—EPCs) versus EPC grade for each age band (left) and attached status (right).

Synthesising the results suggests that building age is a better indicator of actual energy performance, particularly for gas consumption, compared with attached status. The importance of building age for Greater London and energy policy is demonstrated by **Figure 8**, which shows that the bulk of the stock was built before 1945, with most houses built between 1918 and 1939. Most of these interwar houses are likely to be of solid wall construction, and compared with cavity walls, solid brick walls are generally more problematic and costly to insulate post-construction. However, the pre-1914 stock is performing better than predicted by EPCs, which aligns with the findings of Li *et al.* (2015) and Summerfield *et al.* (2019). This suggests that, compared with other solid brick wall houses, the interwar properties would benefit most from energy efficiency interventions.

In addition to the results presented above, tabulated outputs are also provided in Appendix C in the supplemental data online.

5. CONCLUSIONS

Access to actual energy meter data has presented a rare opportunity to investigate energy use in the context of individual houses. In combination with a detailed building stock model and Energy Performance Certificates (EPCs), these have been analysed for trends that may be of use to policymakers and interested parties at the local and national scales. When examined in groupings of attached status with age bands, energy use intensities (EUIs; kWh/m²/yr) of houses, based on recorded fuel consumption, do not always track the energy performance predicted by their EPCs. This is particularly the case for electricity consumption, where there is no correlation between the Standard Assessment Procedure (SAP) rating of the EPC and electrical EUI. Gas consumption is only weakly correlated. These levels of correlation indicate that broad-brush policies, based on EPCs alone, may be limited in their capacity to deliver significant energy conservation, without further investigation of the issue.

Houses built in the period 1918–39 have levels of gas consumption intensity higher than both the succeeding and preceding age bands, especially in semi-detached properties. The phenomenon may be due to errors in assumptions within the EPC method, or it may be the result of peculiarities of the buildings and/or their occupants' behaviour patterns. Whichever is the case, this age cohort accounts for 44% of houses in Greater London and thus constitutes a major portion of the built environment and its energy use, which should have implications for policy development in the sector. Local government energy policies may also benefit from fine tuning, particularly in Outer London, where the bulk of these houses are located.

In terms of building stock energy modelling, the calculation of EUIs provides an enhanced understanding of both gas and electricity consumption in houses. It has been shown that despite having broadly similar built forms, end-terrace and semi-detached houses are statistically separate populations with regards to both gas and electricity consumption. This indicates that modelling these as separate categories ought to improve the accuracy of building stock energy models, at least in the UK.

Having examined only houses, there are still many questions to be asked of the data. Current plans are that research in the immediate future will investigate the relationship between the sale and purchase of houses and their energy use. Further work should also include testing the assumptions within Reduced Data SAP (RdSAP), with particular regard to the *U*-values of walls, allocated according to building age. With 3DStock now expanding to urban areas beyond London, further analyses will be possible, including the comparison of regional variations.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the supply of energy data by the department for Business, Energy and Industrial Strategy (BEIS), under a data sharing agreement. Map data © Crown Copyright and Database Right 2018. Ordnance Survey supplied under licence 311019. © Local Government Information House Limited copyright and database rights 2020. Licence number RDA241 160620. Verisk Analytics Inc. UKBuildings © information supplied under licence: GeoInformation Group, 2019, Licence No. 5360. Valuation Office Agency (VOA) data contain information licensed under the Open Government Licence v1.0. Environment Agency LiDAR data contain public sector information licensed under the Open Government Licence v3.0. Her Majesty's Land Registry data are public sector information licensed under the Open Government Licence v3.0. Ministry of Homes, Communities and Local Government (MHCLG): Energy Performance Certificate (EPC) and Display Energy Certificate data are provided subject to the terms given at: <https://epc.opendatacommunities.org/docs/copyright>.

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COMPETING INTERESTS

The research was funded by the EPSRC, as indicated in the Funding section below. In addition, the authors were provided with access to annualised metered energy data under a Data Sharing Agreement with the UK government's Department for Business, Energy and Industrial Strategy (BEIS) to conduct a study comparing these data with Energy Performance Certificate (EPC) ratings for houses in Greater London. The authors were not remunerated by the BEIS, and the BEIS did not exert any influence on the methods, results, analysis or content of the work described above.

DATA AVAILABILITY

For ministry statistical outputs from the work, see the appendices in the supplemental data online. The datasets upon which the research is based are either publicly available—mostly under the UK government's Open Data licence agreements—or are proprietary and thus available direct from the data owners. The energy data used were provided under a data sharing agreement with the researchers by the UK Department for Business and Industrial Strategy (BEIS) and are thus the property of BEIS.

DATA AVAILABILITY STATEMENT

The various sources of input data are listed in Section 2 of the text and shown in Appendix A in the supplemental data online. The bulk of the data sources were accessed via academic research licences, or under Open Government data licences. The exceptions are the Verisk Geomni UKBuildings dataset, which is available for purchase from the data owner; and the metered energy data, which were provided under a data sharing agreement with the UK Department for Business, Energy and Industrial Strategy (BEIS).

FUNDING

The authors gratefully acknowledge support from UK Research and Innovation through the Centre for Research into Energy Demand Solutions (grant reference EP/R035288/1).

SUPPLEMENTAL DATA

Supplemental data containing the appendices for this article can be accessed at: <https://doi.org/10.5334/bc.79.s1>

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TO CITE THIS ARTICLE:

Liddiard, R., Godoy-Shimizu, D., Ruyssevelt, P., Steadman, P., Evans, S., Humphrey, D., & Azhari, R. (2021). Energy use intensities in London houses. *Buildings and Cities*, 2(1), pp. 336–353. DOI: <https://doi.org/10.5334/bc.79>

Submitted: 15 September 2020

Accepted: 17 March 2021

Published: 09 April 2021

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