ENERGY EVALUATION EUROPE
2020 Conference
Here East, Olympic Park, London
Monday 29 June to Wednesday 1 July 2020
Formerly IEPPEC
Accelerating the energy transition for all: Evaluation's role in effective policy making

Urban density and energy efficiency in the London Building Stock Model

Stephen Evans, Daniel Godoy-Shimizu, Dominic Humphrey, Philip Steadman, Paul Ruyssevelt, Rob Liddiard. Energy Institute, University College London, United Kingdom (steve.evans@ucl.ac.uk)

ABSTRACT

The London Building Stock Model, commissioned by the Greater London Authority (GLA) contains detailed data on every separate domestic and non-domestic building in Greater London. It includes three-dimensional information about buildings including their heights, volumes, wall areas, floor areas and the distribution of activities between different floors. These data are drawn from University College London Energy Institute's existing 3DStock model of London. Within the model information is attached on the ages of buildings, their materials of construction, and (in some cases) their servicing systems. Energy Performance Certificates (EPCs) and Display Energy Certificates (DECs) are also attached to premises and dwellings along with gas and electricity energy consumption.

Buildings in London are responsible for over 65% of the total carbon dioxide (CO_2) emissions attributed to the Greater London region in 2016. Reducing CO_2 emissions that can be attributed to buildings is the key focus of this work in line with the GLA's ambition to dramatically reduce these overall CO_2 emissions; aiming to make London a zero-carbon city by 2050.

Improving the energy performance of existing buildings has to be a key strategy if the overall CO_2 emissions are to be reduced. Knowing the characteristics and current energy efficiency of the building stock is the first step towards reducing direct and indirect CO_2 emissions from these buildings. Collecting the data is one challenge, but making sense of these huge quantities of data is a bigger challenge. Structuring the data can help here and so for this paper we present the evaluation of energy efficiency of buildings in London using urban density to aggregate the data. Energy efficiency is measured from both EPCs and energy consumption. Some of the existing measures that might influence current energy efficiency are then shown at different levels of urban density. Finally, in order to address the improvement of the energy efficiency we quantify the 'potential' improvements of these buildings (according to the EPC recommendations) and hence the suitability of different retrofit solutions, again aggregated by urban density. The results show that energy use intensity decreases as urban density increases; that urban density has some influence on existing efficiency measures and finally that most of the measures of retrofit potential change with increasing urban density.

Introduction

The current Mayor of London is committed to improving the energy efficiency of London's buildings and tackling fuel poverty. In 2018 the Mayor, though the Greater London Authority (GLA) commissioned the London Building Stock Model in order to help enforce the Minimum Energy Efficiency Standard (MEES) which came into force in April 2018. The current MEES regulations prohibit a landlord from privately letting a property that has an Energy Performance Certificate (EPC) below an E rating. Whilst there are exceptions (for example for buildings identified on the national heritage register, known as 'Listed buildings' and places of worship) the enforcement of MEES is planned to increase during the coming years with significant fines to encourage compliance. Furthermore, the government's Green Finance Taskforce recommended that the minimum grade should be increased to a B rating by 2035, which if enforced, would require far more building owners to make improvements to the energy performance of their buildings.

The other aim was that the London Building Stock Model (LBSM) would provide a central database for all energy data collected by the various programmes and policies used by central and local government within London. Buildings are normally quoted as being responsible for around 30-40% of total emissions (Mata et al. 2014) but in London buildings account for a higher proportion, at around 65% (BEIS, 2018).

The LBSM was completed in the Autumn of 2019 and this paper aims to describe the energy efficiency of the building stock of a major global city and its potential to improve this efficiency. Whilst this is possible through using lists and tables of data outputs, the fact that the model is based upon a spatial structure means that more sophisticated analyses and breakdowns are possible. One of these is to look at the spatial patterns within the model and in particular urban density. Using this range of density this paper examines how different measures of energy efficiency vary and finally how the potential to retrofit the building stock changes at different levels of urban density in London.

Background

The aim of this paper is to provide insight into the building stock data, specifically how energy efficiency and other energy related measures change with density. Of particular interest is to see whether buildings in higher density areas perform differently to those in lower densities. Advances in computational performance over the past decade have meant that it is now possible to build detailed spatial models of national building stocks and even pursue the idea of modelling 'digital twins' (real time digital replicas of a physical city). In various sectors, digital twins are used to simulate and test different strategies to deal with problems, carry out diagnostics and identify the best solutions. A team at the Energy Institute, University College London have been working on such a model for a number of years, known as 3DStock. In 2018 the GLA commissioned the LBSM which is itself based upon 3DStock.

Whilst 3DStock and the LBSM would probably require more detailed data before they might justify the label of 'digital twin', the model we describe is far more developed than many existing stock models, which have often been produced by scaling up counts and floor areas of 'typical' premises. In contrast, 3DStock is a fully disaggregate model of the entire building stock within the Greater London region, with both domestic and non-domestic activity classified in great detail alongside the geometry of the buildings, materials, age and energy performance. Energy consumption data is only available publicly at an aggregate level rather than at the individual building level, but even here, for domestic properties at least, it is possible to draw some interesting general conclusions about individual dwellings within the building stock (Evans et al 2018).

The approach presented here to the problem of modelling the energy efficiency of over 2 million buildings, is very different to that used by 'archetypal models' (which rely upon statistical composites of buildings that can be taken to represent typical built forms in the area or region). It is also very different to simply presenting data derived from a sample of buildings within a particular region. We have moved away from projecting small samples onto a large population and towards modelling and measuring the whole building stock, a philosophy more recently referred to as 'energy epidemiology' (Hamilton et al. 2013).

Whilst 3DStock models had previously been built of whole towns, small cities and even parts of London (Evans, Liddiard and Steadman 2016) a model of the entirety of Greater London is a significant undertaking. Greater London covers a region of just over 1,500 km^2 and has a current population of over 8.7 million people. Within this region, according to the Valuation Office Agency (VOA) domestic council tax records for 2017, there are around 1.5 million single household dwellings (houses) and around 1.9 million flats (VOA, 2017). The VOA non-domestic Rating List records show that there are around 245,000 non-domestic premises in Greater London. These non-domestic premises can be broken down by activity classes to show the main activities: For

London, offices are the largest activity by count (37%), followed by Shops (33%), Warehouses (9%), Factories (7%) and Hospitality (6%) with the remaining activities each falling below 2%.

The scope of this study is to distil the data so that it provides a comparable way of describing how the building stock and its energy efficiency changes across the region. To do that we have chosen to use urban density as a measure to gain insight into the data. Density provides a way of measuring the physical buildings right across London without the need to segregate the data into administrative boundaries. Using density, comparisons can be made for a range of building variables.

Methodology

Data sources

Both 3DStock and LBSM are complex models with a multitude of inputs and outputs. There is not the space to describe the methodology within this paper so readers are directed to earlier publications by the authors for more detailed descriptions (Evans, Liddiard and Steadman 2016, 2017, Evans et al 2018). In summary the model is built by matching together a diverse range of datasets from a number of sources including Ordnance Survey, Valuation Office Agency, Energy Performance Certificates (EPCs) and LiDAR (laser measurements from aircraft). Whilst many of the input datasets are not directly spatially referenced they do often contain addresses of the buildings or premises that they refer to. Using the Ordnance Survey AddressBase dataset, which is essentially a national land and property gazetteer with both addresses and the spatial location of these addresses it is possible to match data to Unique Property Reference Numbers (UPRNs) and hence provide a spatial location and a means of linking these datasets together. For example it is possible to assign all the EPCs available for all flats in a particular block of flats and place these inside the geometry representing the footprint of that building. Using other datasets such as LiDAR, it is then possible to determine the building height and volume, and in many cases work out which floor each EPC applies to. These techniques – combining datasets to build a clearer picture of the building stock – are how the core of the model works.

The process is somewhat more complicated than this simple overview makes out since not all buildings have addresses and some institutions like schools, factories and hospitals can be made up of several buildings on a campus, yet have only one main address. However, the model offers feasible solutions to these more complex cases, the details for which are provided in the earlier publications (Evans, Liddiard and Steadman 2016, 2017, Evans et al 2018).

The model is designed to represent a snapshot of the building stock in time. For this particular 3DStock model we chose the date of April 2017 and wherever possible the input datasets like the addresses, the map polygons, the EPCs and the LiDAR data were aligned to as close to this date as was possible. In some cases, such as the most recent LiDAR data, this may date from much earlier, meaning that there will be cases where small parts of the model and the input datasets do not align (for example due to the demolition of buildings or construction of new buildings). However these discrepancies are rare, and represent a very small percentage of the overall model.

Urban density

Density can be measured and referred to in many different ways and for many different purposes. The most common approach in geographical models is to score a value per unit of area, for example population/km^2. For the built environment, the unit of interest might be buildings, dwellings or floorspace with values measured as counts, surface areas, volumes or some other variable (e.g. buildings per ha, dwellings per km^2, or total floor area per postcode and so on). The definition of the boundary of the area part of the density calculation is important since the way it is drawn may influence the outcome of density calculation. For this work we use the postcode boundaries (polygons) available in the OS CodePoint dataset, which encompass on average around 15 properties (though the number can be as low as 1 or sometimes 100 or more). The boundaries usually follow natural and man-made features that determine postal delivery areas. Postcode areas were chosen because they are the smallest statistical unit for which BEIS publish domestic gas and electricity data. The variable that we chose to generate our density measure is the UPRN which can be thought of as an individual address. In more straightforward terms, counts of UPRNs may be seen as being equivalent to the numbers of non-domestic premises and dwellings. Since postcodes cover different geographic area sizes, the postcode boundary polygons have been used to calculate the number of UPRNs per ha. Note that our measure includes non-domestic addresses meaning that for areas dominated by domestic addresses this number can be treated as being roughly equivalent to households per ha, but in areas with non domestic buildings these addresses will also be included in the count.

By using this measure we provide a means of assessing population and building density at the same time. On their own the counts of UPRNs are quite a crude measure, but we have taken this further by comparing volumes of buildings inside the postcodes and aggregating them by built form and activity (for example detached, semi-detached, terraced houses and then houses converted to flats and purpose built flats). These built form classifications are derived automatically in the model so here we have calculated the volume of each built form and expressed it as a percentage of the total building volume per postcode. This way we could show that a particular postcode was made up of say 10% detached houses, 60% semi-detached houses and 20% terraced houses by volume. By grouping this data into density bins based on the UPRNs-per-hectare for each postcode, it was possible to produce aggregate statistics for each bin from all areas in the model. Thus, this quantifies how the building stock varies with density across London. Note that the counts of unique postcodes per bin tends to decline as density increases, with fewer cases being available in the bins that represent the highest densities. For example, the bins up to 100 UPRNs per ha contain on average 6,977 counts of postcodes per bin. At densities greater than 100 UPRNs per ha this declines such that bins in the range 250 to 400 UPRNs per ha have on average 554 counts of postcodes per bin.

The results (in figure 1a) show an interesting pattern which was noted by Mitchell et al (2011), namely that detached houses (shown in red) are dominant in the lowest density areas. As density increases, detached houses drop away and semi-detached housing become the dominant built form at around 25 UPRNs per ha. After this terraced houses (in green) become the dominant built form peaking at around 50 UPRNs per ha. Soon after that flats (in blue) overtake terraced housing and become the dominant dwelling type for the densities above 50 UPRNs per ha. One of the reasons the built form volumes never reach 100% is that we have chosen not to show pure non-domestic building volumes in these charts. The data is there, but if this was shown the charts would be more complex to interpret (but the totals would add up to 100%).

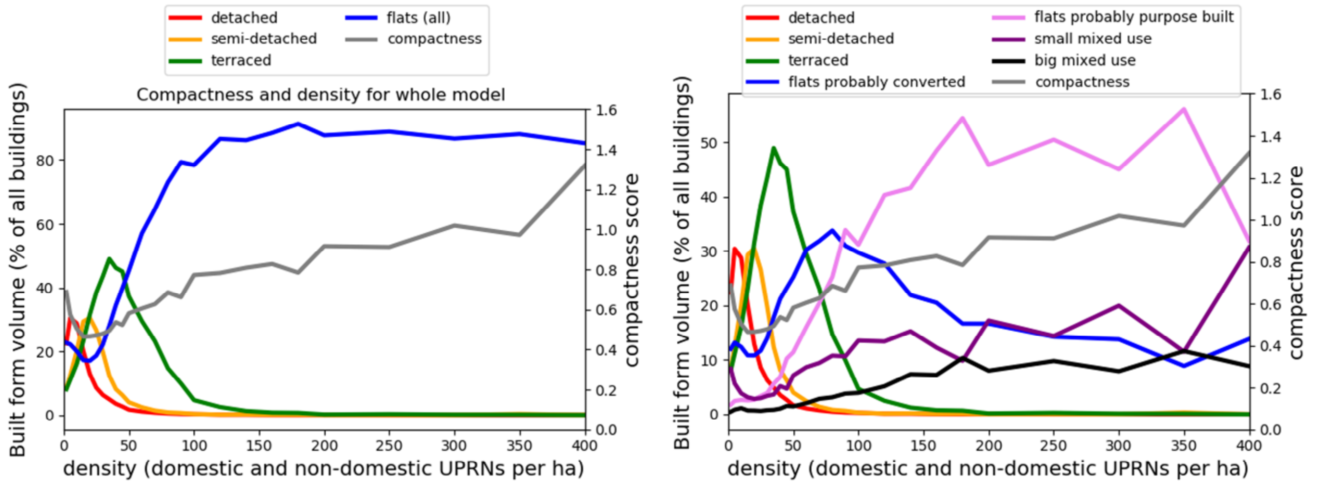


Figure 1a (left) Shows the volumes of different built forms at different levels of urban density. In this example all flats are combined into one single classification (shown in blue). The 'compactness' of the built forms is shown in grey.
Figure 1b (right) shows the same chart but this time splits flats into converted flats and purpose-built flats as well as showing mixed use buildings that include non-domestic activities.
All charts are derived from the 3DStock model of Greater London for the epoch 2017

Figure 1b shows the same data but instead of grouping all flats together as one category they are aggregated by whether the model considers them to be flats in a converted building (such as a house converted into flats) or whether they are considered to be in a purpose-built block of flats. The converted flats behave quite like the other house built forms, in that they peak and then decline, it is just that they peak at a higher density (around 90 UPRNs per ha). This is not surprising since many of these will be flats within converted houses, probably mostly terraced houses. By contrast, the 'probably purpose-built flats' category rises and becomes the dominant built form above 100 UPRNs per ha. Buildings with non-domestic as well as domestic (e.g. flats above shops, shown here as 'small mixed use' and 'big mixed use') also rise as densities increase.

Density, compactness and energy use

The relationship between built form, exposed surface areas and heat loss from buildings (and therefore energy efficiency) has been previously described by several authors such as Steemers 2003. More recently the Intergovernmental Panel on Climate Change (IPCC) pointed out that the structure of a building itself is key to the amount of energy consumed and a "more compact urban form tends to reduce consumption due to lower per capita floor areas, reduced building surface to volume ratio, increased shading, and more opportunities for district heating and cooling systems" (Lucon et al 2014). Evans et al 2018 tested this theory on a smaller 3DStock model using aggregated energy use data and showed that as density increases, energy use intensities for both gas and electricity in the domestic stock decreases. In that paper we used a measure of compactness, which was calculated directly from the geometry of 3DStock. More details can be found in Evans et al 2018, but to briefly summarise, we used a measure of surface area to volume but in a slightly different way. We measured the total exposed area of walls plus the roof area compared to the exposed surface area of a 5 sided cube of the same volume. Using this method, a detached house that forms a perfect cube shape would score a compactness measure of 1. More elongated detached buildings (tall or long) would score below 1. Once buildings become attached, such as semi-detached houses, end terraces and mid-terraces then the compactness value can potentially rise above 1 since some of what previously would have been exposed wall area becomes party wall and therefore doesn't enter into the equation.

We applied the same method to test the results for the whole of London. Since we are interested in aggregated data at the different density levels it is necessary to provide an aggregate of compactness without falling into the statistical pitfalls of averaging the compactness per postcode and then averaging these results depending upon which density bin they are allocated to. To achieve this, we calculated the 'postcode compactness' by treating the overall stock for each area as a single large built form: for each postcode, the actual total exposed surface area of the stock is compared with a cube of the same volume. This value is shown in grey in figures 1a and 1b above. The reader should note that after a small drop below 20 UPRNs per ha, this rises as density increases.

These results alone are interesting, since they give an indication of thermal performance. To produce the results described in this paper, we applied the same model with the same method of aggregating variables at postcode level and then into density bins before generating the aggregate measure for that density bin. This means that all the charts can be compared and contrasted to provide insight into the building stock and its energy performance. For example if a measure shows that average EPC grades are poor at low densities of around 25 UPRNs per ha we can infer that most of these relate to detached and semi-detached houses whilst variables at around 200 UPRNs per ha probably mostly relate to purpose-built blocks of flats and other mixed use buildings. Likewise the association can be made to the compactness scores (and hence an indication of thermal performance).

Domestic EPC data

Introduced in the UK in 2008, domestic EPCs provide a means of understanding the theoretical performance of residential properties. Using a simplified energy model, the standardised 'regulated' energy consumption of each dwelling is estimated based on data collected by EPC assessors as well as several broad assumptions. This modelled energy use is then converted into current A-G 'Energy Efficiency' and 'Environmental Impact' ratings, which reflect the corresponding energy costs and emissions respectively. The data collected by EPC assessors for the model include the physical dimensions of the property, as well as key information including the date of construction, the building envelope, materials and the heating, ventilation and air conditioning (HVAC) plant. A list of suitable improvement measures is also provided (e.g. "add loft insulation" or "replace the existing heating plant with a new condensing boiler"). This list is produced by the EPC software based on the building's current characteristics, and then finalised by assessors based on their knowledge. Finally the simplified energy model is re-run with the suggested improvement measures implemented, in order to produce 'potential' EPC grades. In this way, the EPC database is a source of information on the characteristics and performance of the residential building stock as it is, as well as the potential for improvement.

In early 2017 a large portion of the EPC database was made publicly available. This includes several key building characteristics and the recommendations list, as well as the current and potential EPC grades. This data has been address-matched into 3DStock and has been analysed to better understand how the characteristics of the stock vary across London, as shown in the sections and figures later on in this paper.

To generate the energy-based results we processed the data in two almost identical ways. For the electricity and gas data we only selected postcodes where the number of gas and electricity meters match the number of domestic UPRNs for the postcode. The detailed reasons for doing this are explained in Evans et al (2018) but the main reason was to avoid postcodes where some or all of the dwellings might be electrically heated or where gas might have been supplied in bulk (which can be the case with some large blocks of flats). These selected postcodes were used to generate the density charts below. Importantly this method allows the aggregated gas and electricity data to be matched to aggregate domestic floorspace and thus to work out energy use intensity, as described below. Only by linking this data to a model with floorspace, like 3DStock, can you achieve this type of analysis. For the EPC data a similar approach was taken: Since only around half of dwellings have an EPC at present, only those postcodes which had matched domestic EPCs were included in generating the statistics.

Results

The first set of results in figures 2a and 2b show that for dwellings, the energy use intensity (EUI) (which in this case is measured as kilowatt hours per metre squared per annum ($kWh/m^2/year$)) of both gas and electricity declines as density increases. The drop in gas EUI as density is very noticeable but it is important to not let this overshadow the drop in electricity. Whilst the decline in electricity may appear to be far less significant visually here, it should be noted that it still represents around a 12-15% drop (in line with the findings described in Evans et al (2018)). For gas it appears that gas consumption may be 60% higher at densities below 25 UPRNs per ha compared to at 250 UPRNs per ha. As the authors described in Evans et al (2018), one probable reason for this decline in EUIs as density increases is the increasing compactness of the buildings, as shown in figures 1a and 1b. Interestingly, at the very extreme densities, beyond 250 UPRNs per ha, gas and to a small extent electricity begin to rise again. This may be due to tall purpose-built blocks of flats becoming the main built form at these densities which have been shown to use more gas per unit of floorspace than lower rise buildings (Hamilton et al, 2017).

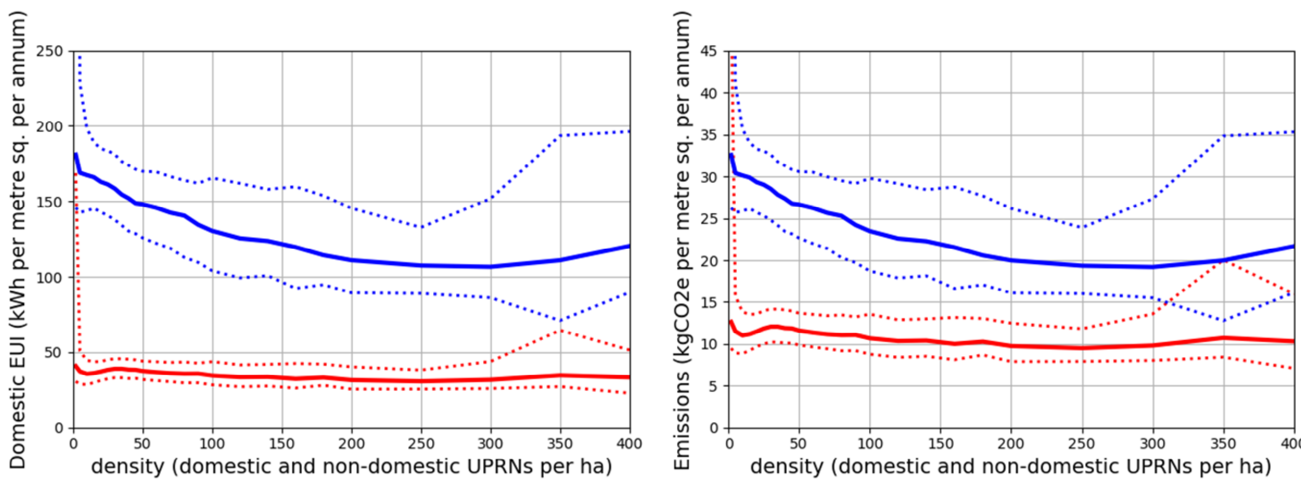


Figure 2a (left) Density and median domestic energy use intensity (EUI) from the 3DStock model. Solid blue line shows median gas EUI, with dotted blue lines indicating upper and lower quartiles. Electricity is shown in red.
Figure 2b (right) Density and median carbon intensity per metre square of floorspace using 0.18 $kgCO^2e$ / kWh for gas and 0.31 $kgCO^2e$ / kWh for grid electricity. Solid blue line shows gas, with dotted blue lines indicating upper and lower quartiles. Electricity is shown in red.

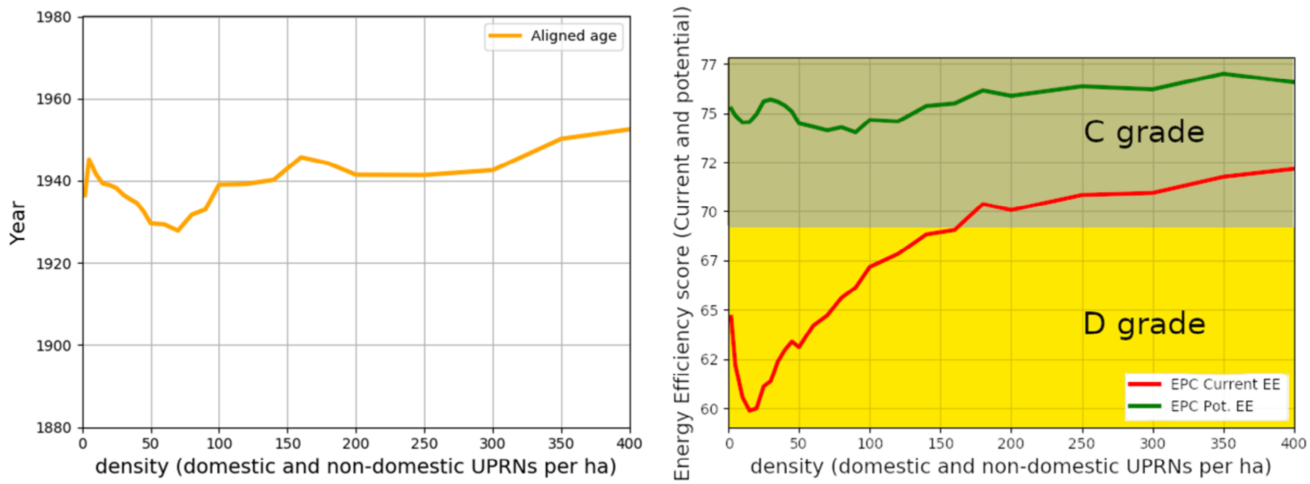
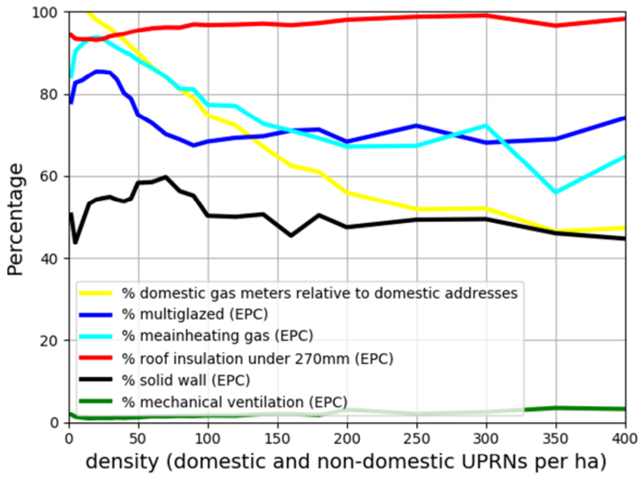


Figure 3 (left) The aggregate age of the dwellings against the density of the stock
Figure 4 (right) Mean EPC Energy Efficiency score (current) shown in red and 'potential' shown in green against density. The EPC bands are shown with the cut off between a D and a C at 69.

The next results shown in figure 3 show how the average age of the stock varies at the different density aggregations. This can be a strange aggregation to understand, but it represents the average age of the stock in each density bin and because a lot of the London building stock is old, the aggregate age for each density bin is rarely more recent than 1950. Whilst there is clearly a small decrease in the average age of the stock at the aggregate level from the lowest densities up until around 60 UPRNs per ha followed by an increase, the reality is that the aggregate age of the stock across the densities is relatively stable. This suggests that building age is unlikely to be a strong driver behind the gas trends shown in Figures 2a and 2b.

Figure 4 takes the same approach but uses two of the EPC variables known as 'Energy Efficiency' and 'Potential Energy Efficiency' and, like all of these graphs, aggregates them in the density bins. Firstly note how after an initial sharp decline at the lowest densities to around 20 UPRNs per ha the aggregate EPC grade steadily rises as density increases. At the aggregate level, this lifts the EPC grade from a D to a C at around 150 UPRNs per ha. The potential energy efficiency (shown in green) has a few wobbles in the data but generally rises as density increases though not as rapidly as the current energy efficiency. This is interesting since it doesn't track in parallel with the current EPC score which suggests that there is more potential to improve EPC grades in dwellings at lower densities than at higher densities. Or to put it another way, the EPC data suggests that it may prove harder to achieve improvements in the energy efficiency of the domestic building stock at higher densities (although at an aggregate level it currently performs better overall than buildings at lower densities). One of the key factors which both helps the current energy efficiency and possibly limits the potential energy efficiency at the higher densities is likely to be compactness. More party walls should mean a lower proportion of exposed walls which itself implies lower heat losses. But at the same time the availability of suitable energy efficiency improvements might be more limited at higher densities, as shown in the paragraphs that follow.



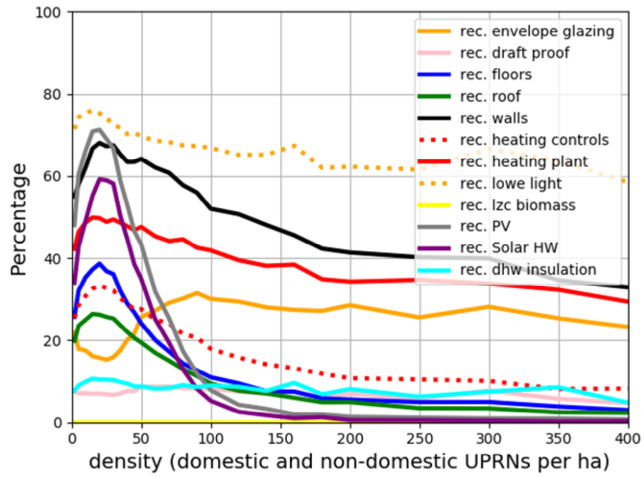


Figure 5 (left) the percentages of some key current EPC variables against the density of the stock. Also shown in yellow are domestic gas meters as a percentage of domestic UPRNs
Figure 6 (right) the percentages of some EPC recommendations against the density of the stock

Following on from figure 4 we chose to interrogate how some of the measures that contribute to the EPC energy efficiency score change with density. Figure 5 shows the results from some of these variables. They showed that low levels of roof insulation (<270mm) are prevalent across the model at around 95% of EPCs, but that there is a slight increase in this as density increases, suggesting that near to 100% of domestic buildings at 300 UPRNs per ha density levels have <270mm of insulation. The proportion of solid walls seems to rise until around 75 UPRNs per ha and then drops slightly. From figure 1b we know that at this density the proportion of terraced houses and converted flats begins to decline which is probably responsible for this decline beyond this density level. The proportion of multi-glazing seems to peak at around 25 UPRNs per ha. This is the point where detached and semi-detached houses give way to terraced houses as the dominant built form. The use of gas as the main heating fuel (according to the EPC) also peaks at around the same density and then declines suggesting that as density increases beyond here, (with the domestic stock becoming dominated by converted flats and purpose-built flats), electrical heating may become more prevalent. This is supported by the measure of domestic gas meters as a percentage of domestic UPRNs which shows a steeper decline to around 50% at densities above 300 UPRNs per ha. The presence of mechanical ventilation on the other hand is very low across all densities, though this rises slightly as density increases.

Finally in figure 6 using the same methods as all of the previous charts, we looked at the EPC recommendations and how these varied with density, bearing in mind what had been observed in figure 4. From this it is clear that almost all of the recommendations decline as density increases. Interestingly, however, some recommendations initially rise to around 25 UPRNs per ha, roughly corresponding with the lowest average current energy efficiency, as shown in Figure 4. Recommendations for domestic hot water insulation and draft-proofing are fairly flat across the full range of densities, possibly because built form and density have little influence on these recommendations. The recommendations for solar PV and solar hot water on the other hand both peak quite sharply at 50 UPRNs per ha before dropping away to very low levels beyond 100 UPRNs per ha. This is presumably because at higher densities, fitting solar technologies becomes less feasible due to shared ownership of roof space and increased overshadowing. Low energy lighting seems to have the highest percentage of recommendations, possibly because this is a relatively simple and low cost improvement. When viewed in parallel with figure 5, the recommendations for improvements to glazing (double glazing/multi-glazing) behaves more or less inversely to the presence of multi-glazing in the EPC itself which is reassuring. Like a number of the other recommendations, improving wall insulation seems to peak at around 25 UPRNs per ha but it declines less steeply after that, compared to the recommendations for solar (PV and hot water). Recommendations for improving the heating plant again peaks at this 25 UPRNs per ha density but then declines as density increases. Recommendations for improvements to heating controls follows a similar trend but with a lower percentage of recommendations.

Conclusions

Buildings contribute to around one third of CO_2 emissions either directly or indirectly (Mata et al. 2014). In capital cities like London this can be closer to two thirds. Finding ways to reduce these emissions is a challenge, but monitoring how this varies across the building stock is an important first step in this direction. Gas and electricity data and EPCs provide one way of examining the energy efficiency of the building stock but there are limitations with what can be achieved with these datasets on their own. When these are coupled with a geometrical building stock model it is possible to carry out more detailed analysis as well as integrating a whole range of other datasets such as the age of the buildings and the different activities occupying the floorspace within these buildings. The data produced can become complex and so simplifying this can help us understand patterns within the data. Using the number of addresses per ha it has been possible to aggregate this data by density. The results from this show that the dominant built form at different levels of density 'ebbs and flows' as detached houses give way to semi-detached, then terraces and finally flats. Using the same density measures and the same model, domestic floorspace can be combined with domestic gas and electricity data to produce domestic energy use per m^2. The general trend is that both gas and electricity EUIs decline as density increases. Some of these changes might be attributed to the age of the buildings but with the data we have, it appears that the aggregate of building age does not show much variability as density changes so there are possibly other causes for this.

Like the gas and electricity data, it appears that aggregate EPCs improve with density although it should be noted that EPCs present modelled, rather than true energy use in their calculations. One of the reasons for the improvement could be that dwellings at higher densities may have more party walls which may reduce heat loss from the dwelling. Measuring compactness from the 3DStock model it can be seen that compactness increases as density increases which will partly be due to increases in party walls and decreases in the surface area of exposed wall relative to building volume. This happens as the dominant built forms shift from detached to semi-detached and then terraced buildings.

The potential EPC grade on the other hand shows some improvement as density increases, but the rate of improvement is weaker than that for current EPC grades. This has some important implications. Firstly it implies that dwellings at lower densities might have a greater potential for improvement than those at higher densities or to put it another way, the EPCs of dwellings at the higher densities, on aggregate at least, are already closer to their potential EPC score than those at lower densities (and hence have less room for improvement).

If we look at the EPCs in detail then we can see that some variables, such as multi-glazing, decreases as density increases. The use of gas as the main heating fuel also declines as density increases. When we look in detail at the recommendations data behind each potential EPC score it is apparent that whilst a few of these show little variation as density changes (e.g. draft proofing and domestic hot water insulation), most of these recommendations peak at around 25 UPRNs per ha before declining as densities rise. Some of this seems logical, such as the potential for solar technologies which may have lower benefits or even legal limitations at higher densities. Others such as improving the heating plant should not logically vary with density and so are harder to explain, perhaps simply reflecting the distribution of gas and electric heating.

It appears that increasing density results in improved domestic energy efficiency. One significant contributing factor to this might be the increasing compactness of the built form. However this benefit appears to become a limitation when it comes to recommending improvements to dwellings since the options for improving the building stock may reduce as density increases. The reasons for this are not clear but compactness probably plays a part here too with overshadowing and more complex tenure and legal ownership questions related to the external building shell of multi-occupancy dwellings. For this reason caution should be applied before encouraging policies that increase the density of dwellings.

It may be that there are other solutions (other than the EPC suggested solutions) to improving energy efficiency of dwellings in higher density areas. As noted earlier in this paper, higher density areas with more compact forms may have "more opportunities for district heating and cooling systems" (Lucon et al 2014). But these technologies that are very well suited to higher density urban settings (such as district heating) may not be an option to the EPC surveyors (for example, to our knowledge, district heating is not an option available within the domestic EPC recommendations). If this is the case then the approaches to both measuring and suggesting improvements to the energy efficiency of higher density dwellings may need to be re-assessed. Decarbonising the building stock is a challenge but according to the work presented here, decarbonising inner urban areas with high levels of density presents a different kind of problem if we are to achieve net zero carbon by 2050. Further research into this area could help to provide more insight here.

Acknowledgments

Data provided by the Valuation Office Agency (VOA) contain public-sector information licensed under the Open Government Licence v1.0. Map data © Crown Copyright and Database Right 2018. Ordnance Survey (Digimap Licence) supplied by the Ordnance Survey/EDINA service. UKBuildings data provided by Geomni. The London Building Stock model was commissioned by the Greater London Authority and delivered in 2020. The authors gratefully acknowledge support from UK Research and Innovation through the Centre for Research into Energy Demand Solutions, grant reference number EP/R035288/1.

References

BEIS (department for Business, Energy and Industrial Strategy) 2018. UK local authority and regional carbon dioxide emissions national statistics: 2005-2016 https://www.gov.uk/government/collections/uk-local-authority-and-regional-carbon-dioxide-emissions-national-statistics (Accessed 21/11/2019)

BEIS (department for Business, Energy and Industrial Strategy) 2020. Postcode level electricity and gas data https://www.gov.uk/government/statistics/postcode-level-electricity-statistics-2016-experimental and https://www.gov.uk/government/statistics/postcode-level-gas-statistics-2016-experimental

Evans, S., Liddiard, R., Steadman, P. 2016. 3DStock: A new kind of three-dimensional model of the building stock of England and Wales, for use in energy analysis. *Environment and Planning B: Planning and Design*. 2017, Vol 44(2): 227-255

Evans, S., Liddiard, R., Steadman, P. (2017): Modelling a whole building stock: domestic, non-domestic and mixed use, *Building Research & Information*, 47(2), 156-172.

Evans, S., Steadman, P., Godoy-Shimizu, D. and Liddiard, R. 2018. Building Stock Modelling and the Relationship between Density and Energy Use. *Proceedings of BSO 2018: 4th Building Simulation and Optimization Conference*, Cambridge, UK: 11-12 September 2018

Geomni 2020. UKBuildings dataset. https://www.geomni.co.uk/ukbuildings

GLA (Greater London Authority) 2018. Solar Action Plan for London. June 2018 https://www.london.gov.uk/WHAT-WE-DO/environment/environment-publications/solar-action-plan (Accessed 10/01/2020)

Hamilton, I., Evans, S., Steadman, P., Godoy-Shimizu, D., Donn, M., Shayesteh, H., Moreno, G. 2017 All the way to the top! The energy implications of building tall cities. *Energy Procedia* 122 (2017): 493-498.

Hamilton, I. G., Summerfield, A. J., Lowe, R., Ruyssevelt, P., Elwell, C. A., & Oreszczyn, T. 2013. Energy epidemiology: A new approach to end-use energy demand research. *Building Research & Information*, 41(4), 482–497.

Lucon O., et al. 2014. Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (IPCC, Geneva), 671–738.

Mata, É., Sasic Kalagasidis, A., Johnsson, F. 2014 Building-Stock Aggregation through Archetype Buildings: France, Germany, Spain and the UK. *Building and Environment*, 81, 270-282

Mitchell, G., Hargreaves, A., Namdeo, A. and Echenique, M. 2011 Land use, transport, and carbon futures: the impact of spatial form strategies in three UK urban regions, *Environment and Planning A.* 2011, Vol 43, 2143-2163

Steemers, K 2003 'Energy and the city: density, buildings and transport' *Energy and Buildings* 35, 3-14.

Valuation Office Agency (VOA). (n.d.) Business rates. Retrieved from https://www.gov.uk/topic/local-government/business-rates

Valuation Office Agency (VOA). (2018) Council Tax statistics. Retrieved from https://www.gov.uk/government/collections/valuation-office-agency-council-tax-statistics