Local energy mapping for urban energy retrofits

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Abstract

This paper presents a localised Geographical Information System (GIS) based mapping approach using publicly available national and local datasets on housing and energy to identify spatially an area for energy retrofit (high energy using and/or high fuel poverty) within a UK town. A GIS-based bottom-up carbon mapping model (called DECoRuM) is then used to estimate energy use, and evaluate the potential of deploying a range of energy saving strategies (fabric improvements, heating system upgrades and solar measures) on a house-by-house level. The local energy mapping approach is found to be effective in visually communicating results to householders, community groups and local authorities for encouraging take-up.

Introduction

It is widely recognised that large-scale energy retrofit schemes can help alleviate fuel poverty (Webber, Gouldson, and Kerr, 2015), meet national carbon targets and improve the local economy (DECC, 2014), but they need to be better targeted, more cost-effective and result in a higher uptake. This paper presents a localised Geographical Information System (GIS) based mapping approach using publicly available national and local datasets on housing and energy to plan mass retrofit and provide targeted low carbon measures across a UK town.

Using GIS systems to map energy use

The aim of urban energy models is to predict the existing energy demand of cities and other urban areas. They also enable the effect of future energy trends to be investigated. Consequently, such models are becoming invaluable to urban energy planners in local authorities to assist in their development of policies aimed at reducing energy consumption and CO_2 emissions (Gadsden et al., 2003).

In the UK, Home Analytics Scotland, managed by the Energy Saving Trust (EST, 2016), is a comprehensive example of GIS based energy mapping designed to help local authorities develop, target and deliver policies and programmes to improve energy efficiency/generation and alleviate fuel poverty. For the purposes of data protection however, Home Analytics can only be accessed by central and local government, registered social landlords or organisation contracted by the those organisations. In contrast, this paper provides a method for bespoke mapping of this information using free publically available datasets. Central and some local authorities also provide mapping of energy related data, which can act as public datasets where applicable to a given purpose or location. These include the Department for Business, Energy & Industrial Strategy (DBEIS) (formerly DECC) ‘National Heat Map’ to support planning and deployment of localised low-carbon energy projects in England by providing maps of heat demand by area (DBEIS, 2016); and Bristol City Council’s (2015) ‘solar potential’ layer to their mapping service which provides information on the viability of photovoltaic installations for planning purposes.

There are a number of GIS based research studies focussing on energy use estimations using bottom-up and top-down approaches. In Massachusetts, USA, utility program administrators used GIS to spatially evaluate energy efficiency program penetration throughout the state. The study showed how GIS can help evaluate where the EE program has been effective and to improve targeting of the program to future customers (Crowley and Brougher, 2014). Another bottom-up method consisted of urban taxonomy characterisation, energy performance assessment, statistical modelling and stock aggregation (Baulio-Gonzalo *et al.,* 2016). In contrast, one top-down method estimated consumption for a city by downscaling via a multiple linear regression model, large datasets including housing characteristics and aggregated energy use (Mastrucci *et al*., 2014). Similarly, another study has exploited Energy Performance Certificates (EPCs) datasets to map energy consumption characteristics in Greece (Droutsa et al., 2016).

The present study takes the next step in identifying an area most in need for retrofit and quantifying the impacts of retrofit options based on need to enable a local council and community group to take appropriate steps to achieve large-scale retrofit. Specifically, top-down sources are first used to spatially identify an area for energy retrofit (high energy using and/or high fuel poverty) within a UK town. A bottom-up carbon mapping model (called DECoRuM) is then used to estimate energy use, and evaluate the potential of deploying a range of energy saving strategies on a house-by-house level, and aggregated to an urban scale. The results are mapped in GIS to communicate findings to residents and local policy makers.

The DECoRuM Model

DECoRuM is a GIS-based toolkit for carbon emissions reduction planning with the capability to estimate energy-related CO_{2e} emissions and effectiveness of mitigation strategies in existing UK dwellings, aggregating the results to a street, district and city level. The aggregated method of calculation and map-based presentation allows the results to be scaled-up for larger application and assessment. The background calculations of DECoRuM are performed by BREDEM-12 (Building Research Establishment's Domestic Energy Model) and SAP 2009 (Standard Assessment Procedure) both of which are dynamically linked to perform calculation in the model. For context, the inputs are more detailed than that required for EPCs; however, the data are collected based on dwelling statistics, external observations, and ideally, occupant-completed questionnaires.

The aggregated calculation method and map-based presentation allows the results to be scaled up for larger application and assessment. To inform the model, actual home and neighbourhood characteristics are gathered from historic and current maps, on-site assessment, occupant questionnaires, and literature describing home characteristics based on age and typology.

The tool is useful for communicating energy related concepts and identifying potential areas for concern and further investigation, including simulation, house assessment and monitoring. Previously, DECoRuM maps have been used to communicate baseline energy consumption and suggestions for energy efficiency improvement measures (Gupta, Barnfield and Gregg, 2015), and climate change impact and adaptation effectiveness (Williams, et al., 2013) to multiple community groups and councils throughout England and Wales.

However large-scale bottom-up modelling of urban areas has some limitations:

- Time required for data collection and entry; home questionnaires are helpful in reducing this initial effort.
- Assumptions have to made about occupant behaviour, although data on indoor temperature set points can be collected via questionnaires or modelled.
- The model does not calculate where specifically a homeowner should insulate walls and whether internal or external insulation is ideal (insulation is simply either solid wall or cavity).

Method

The proposed approach is tested in the town of Bicester in Oxfordshire (UK). The study is comprised of three steps:

1. To identify an appropriate neighbourhood case study area for targeting energy retrofitting measures, top-down energy assessments were performed using publicly available national and local data for Bicester and presented on a GIS platform. Though the datasets could be analysed without mapping, the mapping process assists in communicating the message to stakeholders, e.g. community groups and local councils.
2. The selected area's baseline consumption (among other available indicators) was mapped using both top-down and bottom-up data to inform the model.
3. Retrofit measures and packages tested for the area based on need and acceptability.

Top-down assessment to identify area of focus

The aim of the first step was to identify an appropriate neighbourhood case study area for targeting energy retrofitting measures. The rationale for using the following town-wide datasets was to ensure that the method could be performed easily by local authorities or community groups in any country which may have access to similar datasets. These key top-down datasets included:

Ordnance Survey (OS) MasterMap Topography layer and OS Address-Point: OS MasterMap Topography layer and Address-Point are needed to identify dwelling characteristics (e.g. building form) and to geo-locate and visually communicate CO_{2e} emissions, fuel poverty rating on a house-by-house scale.

EPC dataset: over 6000 dwelling EPCs in a single spreadsheet for Bicester alone, were obtained from the Department for Communities and Local Government (DCLG, n.d.) via Cherwell Council. EPCs include dwelling energy related information (e.g. wall type, insulation, heating system, annual energy use) compiled through domestic energy assessments at address level by trained individuals. The data collection process began in 2008 and is ongoing. EPC data is currently the most detailed and accurate publically available option for displaying energy related aspects for the domestic sector at a dwelling level. Though dwelling level (bottom-up data) is provided, not every dwelling is represented; therefore, the EPC data is assessed in an aggregated sense to provide statistical information for sub-areas of the town.

Sub-national energy consumption statistics (DECC, 2016) and *fuel poverty statistics* (DECC, 2015a), obtained from the Department of Energy and Climate Change: Sub-national datasets are free to use and publically available datasets of metered consumption collected from fuel transporters (DECC, 2015b). The data are aligned with Lower layer super output area (LSOA). LSOAs are zones made up of an average of 1500 residents or 400-700 households with relative social homogeneity. Use of sub-national consumption data at LSOA for a similar purpose can be found in Booth and Choudhary (2011) and Williams et al. (2013).

The method to employing these datasets to arrive at a focal area involved:

1. *Geo-aligning the datasets*: the EPC dataset is a spreadsheet with dwelling characteristic and energy consumption data assigned to individual addresses.

Because the OS Topography layer does not provide the postal addresses for the dwelling location points, the Address-Point dataset was required to bridge the two datasets in GIS so that the EPC data could be mapped.

2. *Cross evaluation of datasets:* Sub-national datasets and EPC data were cross-evaluated as EPCs represent dwelling specific but modelled data and sub-national datasets represent actual but aggregated data. Maps were created to evaluate and demonstrate the appropriate location for further study.

DECoRuM Model – bottom-up baseline analysis

In the DECoRuM model, CO_{2e} emissions are the result of heat loss calculations from fabric and ventilation, estimated energy use from heating, domestic hot water and electricity use as calculated using BREDEM-12 and SAP. Data for calculations include actual house characteristics gathered from historic (Digimap) and current maps (OS Mastermap and Google street view), on-site assessment, home questionnaires responses, EPCs, and literature describing home characteristics based on age and typology (e.g. Tabula/Episcope (BRE, 2014)). Example deductions include:

- occupancy, unless gathered from questionnaires, is calculated from floor area using the BREDEM-12 method;
- street-facing windows and frames are directly observed but all other unseen windows are assumed to be the same;
- wall construction and U-values (unless known, e.g. reported in EPCs) are based on the age of the home where construction methods are well documented (e.g. BREDEM reference tables).

Verification is performed by calibrating the aggregated results to DECC's sub-national energy consumption data for England and Wales at LSOA scale. The results for each household are displayed on a map using GIS; in this instance, MapInfo and ArcGIS. GIS allows any variable to be mapped for visual communication, e.g. kWh/year, CO_{2e} emissions/m^2/year, homes in need of cavity wall insulation, PV suitability, etc.

DECoRuM Model – retrofit measures and packages

Previous research by the authors and others (including simulation and building performance simulation) has demonstrated the effectiveness of retrofit measures and packages for similar home typologies (Gupta and Gregg, 2012; DECC, 2012). These include reduced U-values on building elements, high efficiency boilers, insulating hot water cylinder and pipes, and increased level of heating control. When creating packages, focus on a fabric based package is done to emphasise the importance of implementing fabric first (low-tech demand reduction) measures and (generally) lower capital cost.

Because the DECoRuM model is built from existing conditions, for example, whether there is cavity wall insulation present, the model is immediately capable of calculating the estimated reduction in total annual energy use (kWh), annual CO_{2e} emissions and estimated running costs. To establish whether a measure is valid the following 'reduction assessment method' steps are taken in the model:

1. A simple payback (c) is calculated based on a static reduction in annual running costs (b) and current cost to install a measure (a).

$$a / b = c. \quad (1)$$

2. Install potential (yes / no) must fulfil the following:
   - Is there a reduction in energy use?
   - Is there a reduction in running costs?
   - Is the simple payback period less than the life of the measure?

Results

Stage 1: identification of focal area in need

To isolate areas for further detailed study, the analytical sequence progressed from the entire town of Bicester, to four quadrants of the town, down to specific LSOAs. Figure 1 demonstrates all three levels; first, the town as a whole, second, the hard black line show how the town can be split into 'quads', and third, the LSOA divisions (the quad divisions do not split LSOAs).

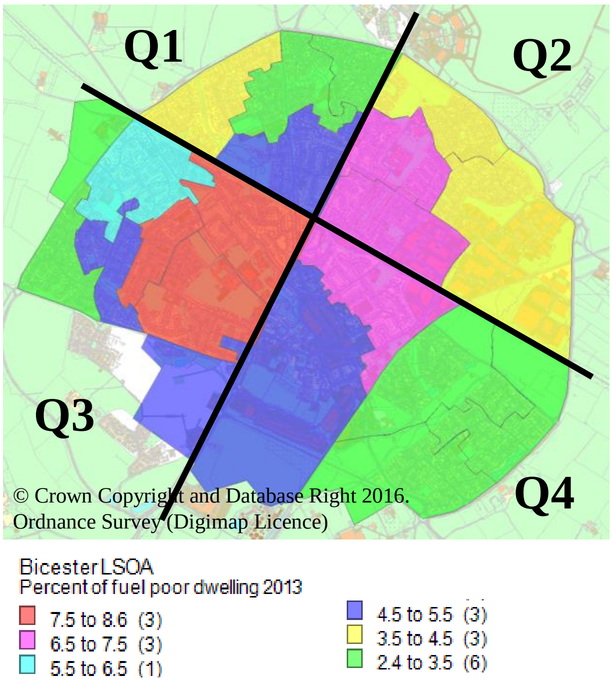

Figure 1: Percentage of fuel poor households (DECC, 2015a).

This sequence was used to evaluate the data for high energy consumption, high fuel poverty, and greater need for insulation. At the town level, sub-national datasets were prioritised for their greater level of completeness and metered (actual data) status. As the analysis mined further down, EPCs were used to verify the sub-national findings and to evaluate details not available in sub-national statistics, e.g. wall and roof insulation. For the entire town there were roughly 5500 valid EPCs, which covered about 45% of each LSOA with the exception of Quad 2 which was under-represented at 35%. At town level, the EPC data showed that:

- Between 50-80 dwellings with known glazing type needed double glazing. Though this is about 98-99% double-glazing for the town, statistics show that in the UK in 2013 80% of homes were fully double glazed and a further 10% had more than half of their window double glazed (DCLG, 2015).
- There are almost 500 uninsulated cavity wall dwellings and 250 uninsulated solid wall dwellings.
- Over 50% of the dwellings with known roof insulation levels in the EPC dataset for Bicester have less than or equal to 150mm of roof insulation; these dwelling could possibly double their insulation levels.
- Over 85% of the town's EPC dataset in heated by gas boiler with radiators, 10% electric storage/portable heating, 1% oil boiler and a total of four (count) homes had heat pumps.

Based on the sub-national data at LSOA level, quad 3 was found to have the highest mean gas consumption LSOA and one of the two highest mean electricity consumption and fuel poor (figure 1) LSOAs. Based on EPC data, quad 3 was found to have the most uninsulated cavity walls in the dataset (198, i.e. 40% of all uninsulated cavity walls for the town). Further down toward LSOA level, 'Cherwell 014C' (figure 2) was selected as the case study pilot neighbourhood because, according to EPC data, it has the greatest percentage of dwellings with annual energy consumption above 300 kWh/m^2 (figure 3).

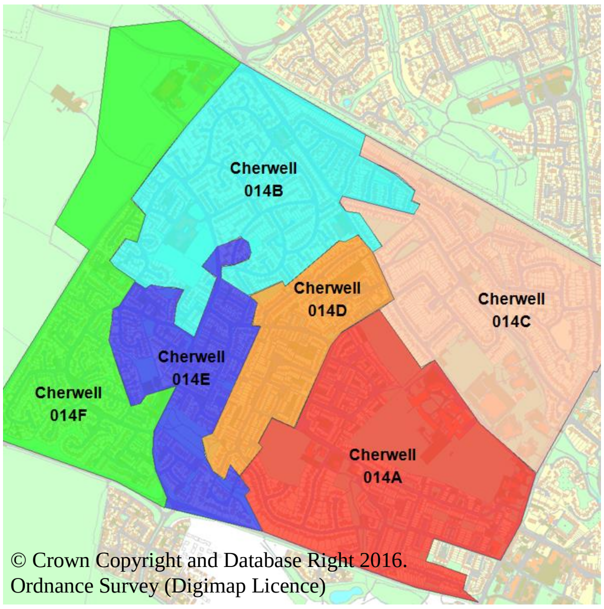

Figure 2: Quad 3 LSOAs.

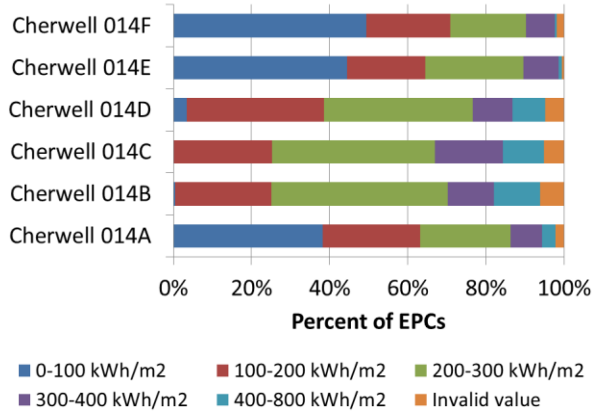

Figure 3: Percentage of EPCs within an energy use range for quad 3 LSOAs.

Stage 2: Bottom-up baseline consumption

Following the identification of the area on which to focus (called Highfield), home questionnaires were distributed in the area. Based on the reach of responses and the deliberate interest in capturing a variety of dwelling types, a definite boundary was defined (figure 4). As can be seen, there is overlap into other important LSOAs.

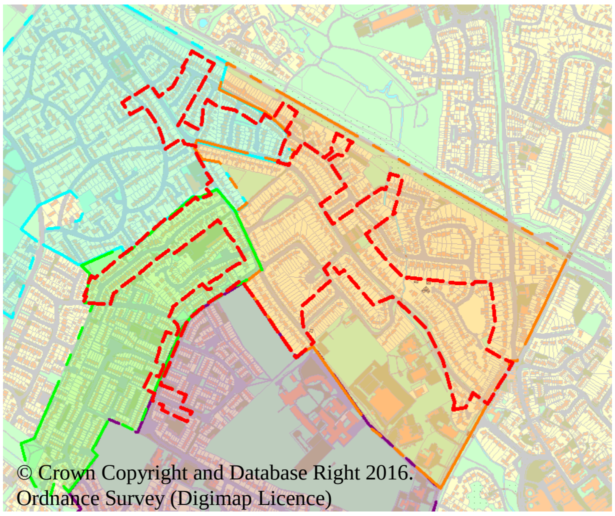

Figure 4: Final modelled area (in red)

The final area contains 627 dwellings, of which there are 222 EPCs and 58 questionnaire responses. Dwellings range in age from 1920–2010. In the mapped area, semi-detached dwellings (most common in the UK) represented 59%; in contrast, this is 25% for the town. Since the town has a fairly equal spread of detached, mid-terraced and semi-detached housing, learning from all forms would have meaning for spreading the findings out beyond the defined boundary.

Figure 5 shows the age-band spread of the housing in Bicester as compared to Highfield. The town has a roughly equal spread of age-bands after the 1950s. In contrast, the Highfield area appears to have mainly developed between the 1930s – 1970s. Highfield also includes a notable area of post-1996 development.

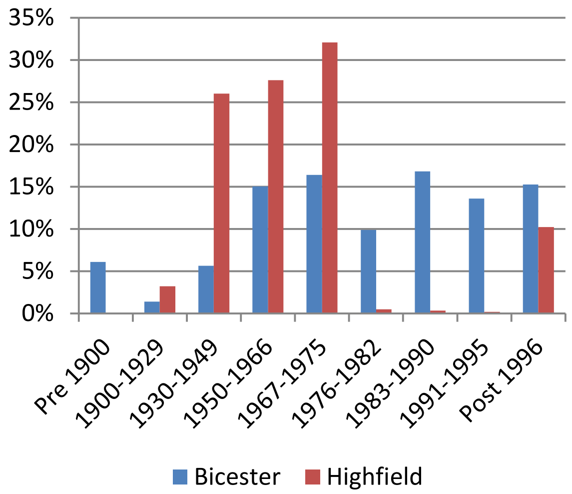

Figure 5: Age-band assessment

The annual energy consumption in Highfield varied between 6,000kWh to 42,000kWh with 110 dwellings consuming between 21,000–25,000kWh per year (energy bills $1,550–2,050/year; CO_{2e} emissions of 5.4-6.8 tonnes/year). Figure 6 shows the baseline map for annual CO_{2e} emissions. Note that only a close-up of a section of the map is shown due to limited space.

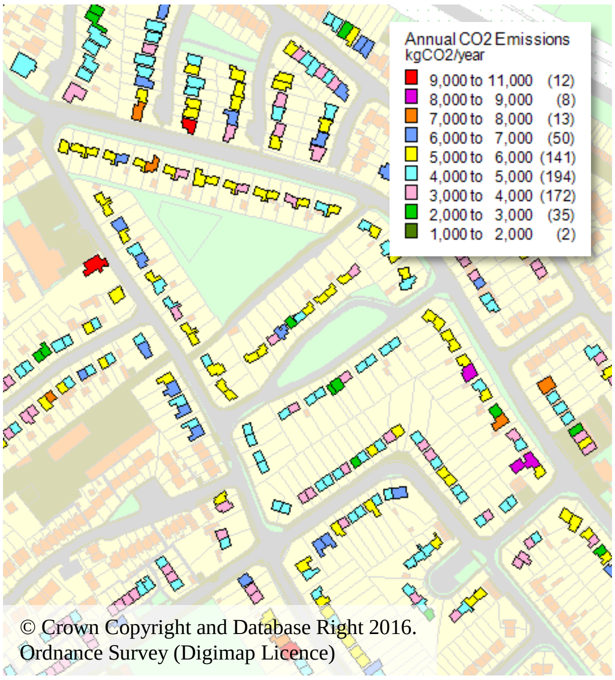

Figure 6: Baseline map – annual CO_{2e} emissions

Stage 3: Retrofit opportunities

For the mapped area, solid wall insulation followed by cavity wall insulation produced the greatest mean reduction in carbon emissions (30% and 25% respectively). Loft and floor insulation, new condensing boiler, heat pumps and photovoltaic panels resulted in mid-range reductions with means ranging from 12-17%.

The model is built using known (questionnaire response) or externally gathered information; therefore, it is recommended to 'verify need', for some measures, e.g.:

- 363 dwellings could potentially install cavity wall insulation and
- 542 homes could potentially install ground floor insulation.

The selected measures were grouped into packages as shown in table 1.

Table 1: Retrofit packages

Fabric package	**Fabric & heating package**	**Fabric, heating & solar package**
Wall insulation (cavity or solid)	**Fabric package +**	**Fabric & heating package +**
Loft insulation	New condensing boiler or ASHP or GSHP	Photovoltaic system
Floor insulation	Hot water cylinder insulation	Solar hot water system
Double glazing	Hot water cylinder thermostat	
Draught proofing	Pipework insulation	

The reduction assessment method revealed that eight dwellings in total could install the complete fabric package and six of these dwellings are 1930s–1960s semi-detached. Four hundred and ninety two dwellings could potentially install a condensing boiler but only nine dwellings could pass the reduction assessment for air source heat pump (ASHP) and 20 for the ground source heat pump (GSHP). Gas dominance in Highfield and the seven-year limit on the Renewable Heat Incentive (RHI) are significant factors for the reduced potential to install ASHP and GSHP. Finally, though 577 dwellings could install photovoltaic panels, only six dwellings could justify the installation of solar hot water (SHW) systems. SHW is also subject to the seven-year maximum collection period for the RHI, which limits the return on investment for the systems. Photovoltaic panels still appear to be an effective measure even considering a significantly reduced Feed-in Tariff (FiT), (generation tariff in 2016 is about 90% less than when FiT began in 2010 (CE Ltd., 2016; Ofgem, 2016)).

The reduction assessment method revealed that six dwellings in total could install the complete fabric, heating, and solar package. Four of these dwellings are 1930s–1960s semi-detached. Older dwellings, e.g. 1930-1949 semi-detached (most common type in the area), have shorter payback periods due to greater need for improvement, and are therefore more likely to benefit.

Overall, a full fabric, heating and solar package emerged as the most effective given that reduction percentages are almost doubled when compared to fabric package results. Table 2 shows the results of the packages on energy consumption and simple payback period.

Table 2: Retrofit package results

	Fabric package	**Fabric & heating package**	**Fabric, heating & solar package**
Number of partial or full retrofit packages	543	453	412
Mean % of energy use reduction	29%	41%	46%
Mean simple payback period	10 years	9 years	12 years

Discussion of modelling results

One interesting initial finding is that when the mean EPC data for LSOAs Cherwell 014B, 014C and 014D are compared to the sub-national figures (2014), there is an over-estimate of between 3,000-4,000 kWh/yr (16%) in the EPC figures. Due to the modelled nature of EPC data, the incomplete dataset was not expected to align with the (metered) sub-national data; furthermore, it reveals the importance of recognizing the differences between these two datasets:

- The EPC dataset can have EPCs up to eight years old in 2016. As compared to the sub-national energy data which is for a single selected year. It is possible that dwellings with old EPCs could have made upgrades and reduced consumption. In addition, dwellings could have changed occupants (including change in tenure, family size, behaviour) since the EPC was registered which can change the consumption results.
- EPC data are calculated using a reduced model whereas, the sub-national energy data are annualised estimates of consumption for all Meter Point Reference Numbers in the specified sub-national boundary (DECC, 2015b).
- The model assumes that occupants heat their houses to 21°C (living rooms) and 18°C (other rooms). However, many households are likely to heat their homes to different temperatures (CSE, 2015). The mean of questionnaire responses actually showed living room set points at 19°C.
- Appliance and hot water requirements for EPCs are made using simplified equations relating to the number of people in a household (CSE, 2015).
- The sub-national domestic energy datasets are only available for gas and electricity whereas, EPCs can include oil, coal, biomass, etc., heated dwellings.
- Due to the nature of the EPC process (only required when a dwelling is built, sold or rented (GOV.UK, 2015)), EPCs only represent approximately one-third of the addresses (i.e. electricity meters) in each LSOA (about 200 EPCs to 600 meters).

The reasons above show why it was important to gather bottom-up information on a selected number of dwellings to provide baseline and retrofit potential conclusions.

Using the urban model for large-scale energy retrofits

This section describes the possible ways in which the DECoRuM model can be used for making decisions for undertaking large-scale retrofits. Possible methods to approach a large-scale retrofit can include:

1. Identify and calculate the retrofit potential of most common dwelling types in the area,
2. Identify and calculate the retrofit potential of dwellings that require a specific package of common measures, or
3. Identify hot spots of energy consumption or fuel poverty.

Method 1: Most common dwelling types

The four most common dwelling types are identified as:

- 1930-1949 semi-detached (23%) (type A)
- 1950-1965 semi-detached (19%) (type B)
- 1966-1976 semi-detached (15%) (type C)
- 1966-1976 detached (9%) (type D)

The first most common dwelling type incidentally also has the greatest mean energy consumption ($279 kWh/m^2$). This positions dwelling type A as a worthwhile starting point for retrofit in the area. In addition, common dwelling types are often grouped together making mass retrofit using this method easy to achieve. Figure 7 shows the collection of dwelling type A in the case study area (outlined in black).

Figure 7: Energy consumption of type A dwellings

Table 3 shows the impact of the fabric, heating and solar retrofit package on the common dwellings types. Clearly retrofitting beginning with type A will benefit the area most, where the most dwellings will have a high reduction in energy consumption and running costs.

Table 3: Fabric, heating and solar package results

	Type A	Type B	Type C	Type D
Mean reduction in energy use (kWh)	12,493	11,025	9,921	12,572
Mean reduction in running costs	£795	£763	£669	£839
Mean simple payback	11 years	13 years	12 years	12 years
No.of dwellings install full or partial package	2 full 128 part	2 full 73 part	0 full 67 part	0 full 42 part

Method 2: Most common improvement measures

Figure 7 shows the dwellings (in green) that potentially need wall, roof, floor insulation, condensing boiler, and PV. In red are the dwellings that do not need the package (lack of need has a higher confidence due to data collection method, i.e., need is assumed given dwelling age and characteristics unless an upgrade is proven to exist). The circles of green dwellings indicate clusters of dwellings, which would be easy starting places using the common measures method. Note that the dwellings within the circle at the top of figure 8 are type A dwellings. If a mass retrofit of all of dwelling type A involves too many dwellings at one time, combining method 1 and 2 can be effective in concentrating efforts on smaller area with more focus.

Figure 8: Retrofit package potential for dwellings

It is important to note that there are many combinations of carbon reduction measures and they do not necessarily need to follow the packages as defined in this study.

Method 3: Identifying hotspots of energy use

In contrast to the above methods, baseline energy consumption data can be assessed for areas of high-energy consumption (figure 9). Alternatively, hot spots of fuel poverty or effectiveness for measures can also be mapped, e.g. mapping dwellings where cavity wall insulation is most effective in reducing energy consumption. Figure 8 shows the annual energy use ranges, and a row of terraced dwellings on the map with energy consumption in the highest ranges. This area would be a recommended as a good place to focus for high impact retrofit action, using this method.

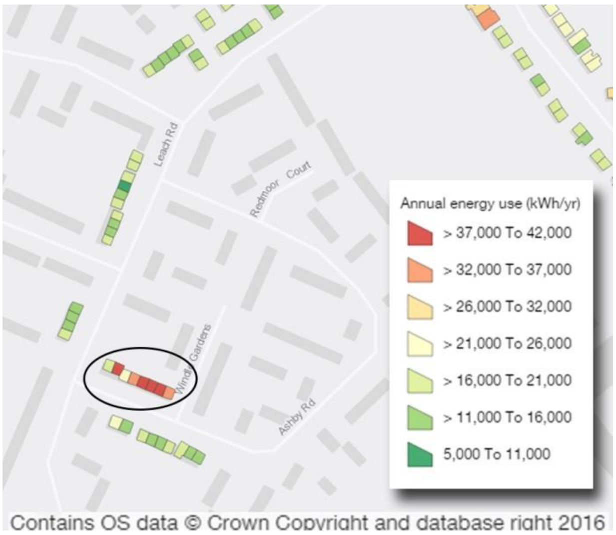

Figure 9: Energy consumption for a hot spot

Conclusion

This study has helped address the challenge of collecting data on which to target, baseline and predict the impact of retrofit efforts in the domestic sector. The process described here is considered to be a targeted and cost effective way to influence higher uptake of large-scale energy retrofits to help alleviate fuel poverty, meet national carbon targets, and improve the local economy. The process provides the ability to collect data, model map and ultimately aggregate housing retrofit activities to minimise installation costs. Spatially mapping the potential for energy improvements in a geographical area is also found to be visually effective in communicating results to householders, community groups and local authorities to encourage take-up.

Local energy mapping has emerged as a valuable approach for strategic planning, evaluation and implementation of community and neighbourhood scale domestic refurbishments by rapidly measuring, modelling, and mapping and managing energy use and CO_{2e} emission reductions on a house-by-house level. Bespoke site-specific mapping of current energy consumption and visualisation of the potential for energy savings can also enable the uptake of carbon reduction measures. The model can help local authorities, community groups and householders to prepare for any national retrofit programme.

Future expansion of this work includes the development of DECoRuM-Adapt, a next step for DECoRuM created to assess future climate impact, overheating risk and adaptation measure effectiveness. The assessment of the climate change risk allows for the further evaluation of mitigation measures to optimise the home's refurbishment to be thermally comfortable now and in the future. To further benefit research in this area, future work in urban modelling would include analysis of modelling outputs with socio-economic data to track the effect of refurbishments on fuel poverty.

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