The Carbon Footprint of UK Cities:

4M: Measurement, Modelling, Mapping and Management

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The City of Leicester

Introduction

The planet is threatened by the emission of human-made greenhouse gasses, and in particular carbon dioxide (CO_2) from the combustion of fossil fuels. In 2009, average annual CO_2 emissions were 4.1 t CO_2 per person worldwide, although in developed countries this was substantially higher at 11.5 t CO_2 per person (IEA, 2009). Atmospheric CO_2 concentration has reached 380 ppm globally, with levels increasing by 1.9 ppm annually between 1995 and 2005 (IPCC, 2007). The world's population currently stands at 6.8 billion and is set to rise to c.8 billion by 2050 (PRB, 2009). In 2008, for the first time, over half of all people lived in cities and by 2030 this is expected to rise to nearly two-thirds (UNFPA, 2007). The high density of people in cities, who use energy for transport, food, and consumer goods and services, make them major contributors to global greenhouse gas emissions. The need to reduce CO_2 emissions from cities is clear.

International negotiations to curb emissions have had mixed outcomes, but notwithstanding, national and sub-national initiatives proliferate. Policies and economic instruments to cut CO_2 emissions need to operate in a manner that preserves, or even enhances, cities' functioning and environment.

Transport emissions have to be curbed without impinging on necessary travel, building energy use needs to be controlled without rendering them inoperable, and emission reduction practices need to impact as little as possible on key ecosystem services[1]. Importantly, emissions reduction in all of these areas can go hand-in-hand with improvements to lifestyles and well-being: reduced traffic improves air quality and therefore human health, more energy efficient buildings lower fuel costs to occupants, and green spaces can sequester carbon whilst improving the aesthetic environment and human health and well-being. Thus, a low carbon city can be a cleaner, quieter, healthier and more enjoyable city.

The 4M project is examining these issues by estimating key components of the carbon footprint (Wiedmann & Minx, 2008) of the city of Leicester in the UK. The project adopts a multi-disciplinary perspective and is being progressed through collaboration between researchers from five UK universities and Leicester City Council. This enables a rounded view of proposed carbon reduction initiatives to be evaluated in the real social and economic context of a functioning and dynamic city. The project has four activities, measuring, modelling, mapping and managing carbon emissions - hence 4M.

The project team are measuring the carbon emissions from buildings and transport, as well as biological carbon storage and sequestration in soil and vegetation. The aim is to establish a strategy by which city authorities can measure the changes in carbon emissions and sinks over time, and to create a workable, bottom-up, methodology for urban carbon foot-printing. Models underpinned by the measurements enable the relationships between emissions and human activity to be understood and mapped. The models also enable the likely impact of carbon management practices to be predicted. Although the effect of individual management interventions can be small, added together and over time many small additive interventions can deliver deep cuts in carbon emissions.

The 4M Aims and Objectives

Aims

- Provide a methodology, data sources, models, data collection techniques, analysis methods and validation approaches, that can be used to benchmark and manage the carbon sources and sinks in UK cities;
- Produce ways of representing carbon sources and sinks in a form suitable for visualisation and interpretation by policy makers and other stakeholders;
- Generate key components of the direct carbon footprint for the City of Leicester and assess the likely impact on it of some municipal building energy, ecosystems and traffic management strategies.

Objectives

- Map the actual carbon produced by both domestic and non-domestic buildings in the City of Leicester through the acquisition of existing data, the collection of new data and the development of people-sensitive models of energy use;
- Predict the likely impact on the carbon footprint of proposed (and other) deployments of a district combined heat and power scheme, domestic micro-generators and non-domestic energy efficiency measures;
- Map the carbon emissions due to vehicles travelling in the City of Leicester road network;
- Predict the effects of driver behaviour, new vehicle technologies, intelligent transport systems and novel policy interventions on urban transport-related carbon;
- Map the carbon pools associated with green spaces in the City of Leicester;
- Determine the impact of alternative building, traffic and green-space management practices on the urban carbon pools;
- Explore the implications of different carbon emissions reduction initiatives targeted at households from different socio-economic groups;
- Assess the scope and impact of local policy initiatives and thus gain an insight into the rate at which carbon emissions could plausibly be reduced.

Funding

The four year project began in March 2008 and is supported by the UK Engineering and Physical Sciences research Council (EPSRC) through grant EP/F007604/1 'Measurement, Modelling, Mapping and Management 4M: an Evidence Based Methodology for Understanding and Shrinking the Urban Carbon Footprint'. The 4M consortium has 5 UK partners: Loughborough University (lead), De Montfort University, Newcastle University, the University of Sheffield, and the University of Leeds. The project has 8 active academics, 10 funded research assistants and 7 contributing higher degree students. It is actively supported by Leicester City Council and an international advisory panel who help to steer the direction of the research.

UK Carbon Emissions and Policies

The UK currently has a population just over 61 million (ONS, 2009), with approximately 58% living in cities and 80% in urban areas, the latter of which comprises 11% of land cover. Around 56 km^2 of countryside is urbanised each year (Schoon, 2001). The population is expected to rise to about 73 million by 2033 (ONS, 2009). In 2006, the UK was the 8th largest gross emitting nation, at 9.2 t CO_2 per person (UN, 2010). Of these emissions, business, homes and transport account for about 89%: 34% from business, 28% from homes, and 27% from surface transport (DECC, 2010a), but road traffic is increasing at around 2% per year (SDC, 2010).

The UK government, through the Department of Energy and Climate Change (DECC), has set a target of 80% reduction in UK greenhouse gas emissions on 1990 levels by 2050 (Great Britain, 2008). This puts energy demand reduction and low-carbon energy supply at the forefront of managing future urban environments. The Committee on Climate Change (CCC) has now set legally binding carbon budgets for the first three five-yearly periods up to 2022 (CCC 2008), and produced its first report on progress against these budgets (CCC, 2009). Decreasing dependency on centrally supplied energy to heat, cool and light buildings and moving towards less polluting transport systems are key components of the CCC carbon reduction pathway. Recognising the need for comprehensive data by which local authorities and others might monitor emissions, the government, through DECC, has begun to publish measurements of the carbon emissions from buildings and transport (DECC, 2009a)[2].

The buildings sector has been the target of a number of recent policy initiatives. The building regulations that set minimum carbon emissions standards will be radically tightened such that, by 2016, all new homes must be zero-carbon (CLG, 2006). However, the existing 25 million homes are the important target for emissions cuts and the great British refurbishment aims to retrofit 7 million homes by 2020 (DECC, 2009b), a truly mammoth task. It is planned that the initial cost can be met by pay-as-you-save (PAYS) grants, tied to each house, which will be paid off by successive occupants of that property through their fuel bill (HM Government, 2010). To encourage the installation of new and renewable energy technologies, from April 2010, feed-in tariffs (FITs) have guaranteed householders income from each unit of electricity exported to the grid (DECC, 2010c). The roll out of smart meters[3], such that all homes will have them by 2020 (DECC, 2009c), will enable such a scheme. The renewable heat incentive (RHI), intended to begin in April 2011, will, if it proceeds, credit households for the installation of new heating technologies such as solar water heating (DECC, 2010d). However, very little work has been done to determine the likely uptake of such schemes, what might be done to promote them (there is a valuable role here for local authorities) and, importantly, the true impact they might have on carbon emissions.

There is an ambition that all new non-domestic buildings should be zero carbon from 2019 (HM Treasury, 2008). Whether one imagines this to be possible or not, delivering carbon reductions of 80% by 2050 requires radical improvement to the energy efficiency of the UK's existing c1.8million non-domestic buildings. The EU Energy Performance of Buildings Directive has been in force since 2002. Proposed modifications, currently out for consultation, include the requirements that all refurbished or extended buildings and all buildings owned by public authorities,, or frequently visited by the public, that are over 250m^2 should be monitored and a Display Energy Certificate showing the annual energy use (or operational rating) should be prominently displayed (EU, 2010). The current average rating of UK non-domestic buildings is 'E'; if an 80% cut is to be achieved in this sector, the average rating must improve to 'C' by 2020 and 'A' by 2050 (Carbon Trust, 2009)[4]. But given the diversity and complexity of the geometry, construction, and energy services of many non-domestic buildings, and restrictive tenure and lease arrangements, together with the often short occupation periods, this is daunting task. Clearly, if local authorities are to manage carbon emissions effectively, they need specific targets and planning support tools for the non-domestic sector.

The UK Department for Transport has made sustainability central to their plans for 2014 and beyond, as outlined in the 'Towards a Sustainable Transport System' (DfT, 2007) and the 'Delivering a Sustainable Transport System' (DaSTS) publications (DfT, 2008). These are associated with the roll out of Automatic Traffic Management on motorways, electric vehicles, shifts towards greater public transport use, promoting cycling and walking, green travel plans and intelligent transport systems. The Commission for Integrated Transport has made recommendations to deliver cost-effective carbon savings from transport by 2020, aiming for a 14% reduction against 1990 levels (CfIT, 2007). The modelling of traffic flows in UK cities is relatively well developed, driven primarily by congestion and air quality concerns. These same models can be used to estimate carbon emission but the figures are crude, failing to account for the large difference in emissions between free-flowing (off-peak) and on-peak travel, and the types of vehicle on the move at different times. These weaknesses need to be overcome to create appropriate tools for designing effective low carbon transport policies.

The need to cut emissions from transport and buildings is self evident. However, in order to meet national and international obligations to produce national inventories of greenhouse gas emissions by sources and removal by sinks, as well as meeting reporting requirements under the Kyoto Protocol, UK biological carbon emissions and sequestration arising from different land uses, land use change and forestry must also be accounted for (Dyson et al, 2009). This includes estimating the carbon loss associated with the conversion of land through the process of urbanisation (e.g., from areas of agricultural production, grassland, forest). Yet, once land is considered to be urban, biological carbon density at equilibrium is assumed to be zero (Dyson et al, 2009). Contrary to this assumption, recent research conducted in North America (e.g., Nowak & Crane, 2002; Pataki et al, 2006; Pouyat et al, 2006) has suggested that urban carbon pools associated with vegetation and soils warrant closer appraisal as, although small compared to overall carbon emissions, they could provide a valuable contribution reducing net emissions. Nonetheless, findings from North America cannot simply be extrapolated to Western Europe, as the patterns of urbanisation are substantially different. In North America, the trend has been towards progressively more dispersed patterns of settlement referred to as 'sprawl', which are driven by the construction of large, low density residential developments beyond the urban periphery (Hansen et al, 2005). In contrast, within the UK and other parts of Europe, there is a tendency to densify existing urban areas, with remaining urban green space being built upon, particularly domestic gardens (a phenomenon commonly referred to as 'back-land development' or 'garden grabbing'; Burton, 2000; Goode, 2006; ODPM, 2006). The 4M project will be the first to determine the value of biological carbon pools within an urban area in Europe.

It should be evident from this overview that UK carbon emission targets and trajectories have been set and policies, which will work towards achieving them, put in place. However, the emissions reductions required at regional or city scales have not been prescribed and it is unlikely that all cities can realistically achieve the same emissions cut over the same time period and at a similar cost. So, whilst local government and city authorities are in the front line of the national struggle to cut emissions, there is no fair and transparent system for determining the reduction targets for individual urban areas, a time-frame over which these reductions must be made, and the probable costs. City authorities desperately need reliable data and models to help them establish realistic carbon emission targets, emission reduction trajectories, and acceptable and robust policies for meeting these.

The City of Leicester and Emissions Reduction

Leicester is geographically central in England. With a resident population of 280,000 in 2007, living in over 110,000 homes (ONS, 2010), and with 70,000 or so non-domestic buildings it is the UK's 15th largest city. The households in the city cover a wide range of socio-economic categories, from affluent to disadvantaged. Since 1991 the population has expanded by 3.5%, compared to the national average of 4.5%. The city, and thus the 4M study area, has a clearly defined edge with major transport arteries connected by an inner, middle and outer ring road (Figure 1)[5] and good transport links via the M1 motorway (to Nottingham, Derby and Northampton) and the M69 (to Birmingham). London is just ninety minutes away by mainline rail and an international airport is just 32 km from the city centre.

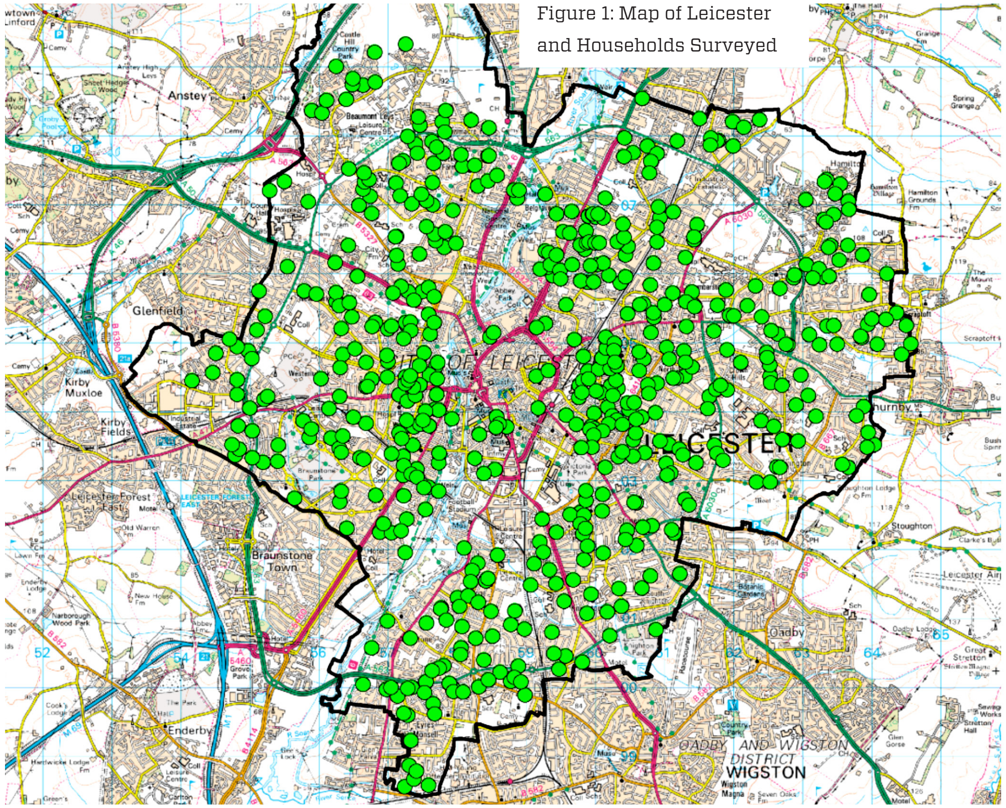

Figure 1: Map of Leicester and Households Surveyed

Green space, which accounts for 57% of land cover within the local authority boundary, includes individual street trees, road verges, public parks, allotments, riparian zones, golf courses, schools' grounds and brownfield sites. The city council is responsible for maintaining and managing approximately 23% of this 41.7 km^2 of green space. Domestic gardens constitute just over a quarter of total land cover (Loram et al, 2007), which is comparable with other UK cities.

The city council has a longstanding commitment to combating climate change. In 1990 it was voted Europe's first environment city and during the 1990s was part of the International Cities for Climate Protection network. Historically, the council's action on environmental issues has primarily focused on sustainable energy use and identifying the non-energy benefits of energy efficiency and renewable energy policies. The city council's climate change strategy (City of Leicester, 2003) declares *"a target of 50% reduction on 1990 levels of CO$_2$ emissions by 2025"*. The council *"recognised the importance of having an accurate emissions inventory in order to identify the main users of energy, the effectiveness of measures adopted and the progress towards targets"*. However it was also noted that *"since 1996 there has been much greater difficulty in obtaining good quality data at a high enough resolution to inform the modelling"*.

The city council has built a strong working relationship with UK universities, and, importantly, has contributed data and information to their research endeavours. Since 1987, the instrumented City (iC) initiative has recorded traffic flows and delays, and since 1997 data from 13 indicative pollution monitors has been collected. The iC has provided a solid foundation for work at Leeds University and latterly Newcastle. Several collaborative partnerships, between universities and Leicester City, County and District Councils, has resulted in the implementation and evaluation of priority public transport corridors, bus tracking devices to provide real-time information at bus stops, and personalised messaging to travellers (Chen & Bell, 2002). Since 2001, the city council has monitoring half-hourly energy and water use in over 300 public buildings. These data are available for analysis by De Montfort University (Brown et al, 2010).

Since April 2008, the performance of local authorities throughout the UK has been measured against 198 National Indicators (NI). Local authorities agree priorities for improving the local area in conjunction with other public sector agencies, through three yearly Local Area Agreements (LAAs). These contracts with central government include no more than 35 negotiated NIs as well as 18 other statutory targets. Leicester's LAA for 2008-11 includes NI 186 - Per capita CO$_2$ emissions in the local authority area, with a city target *'To reduce emissions to 6.1 t CO$_2$ per person by* 2011' (One Leicester, 2009) as well as NI 188 - Adapting to climate change, *'To reach level 4 of 5, in developing and maintaining an action plan, by 2011, from a baseline of level 2 in 2008'* and NI 167 - Congestion – average person journey time per mile during morning peak flow, *'To only increase to 4.89 minutes per person mile, by 2011, from a baseline of 4.6 minutes in 2004/5'*. The DECC publishes statistics that chart progress against NI 186. These figures exclude emissions over which local authorities have no influence, such as motorways and some installations covered by the EU emissions trading scheme. Over the period for which figures are available, Leicester has reducing annual emissions from 7.1 t CO$_2$ per person in 2005, to 6.96 and 6.6 tonnes CO$_2$ in 2006 and 2007 respectively (DECC, 2009d). The emissions for 2007 are

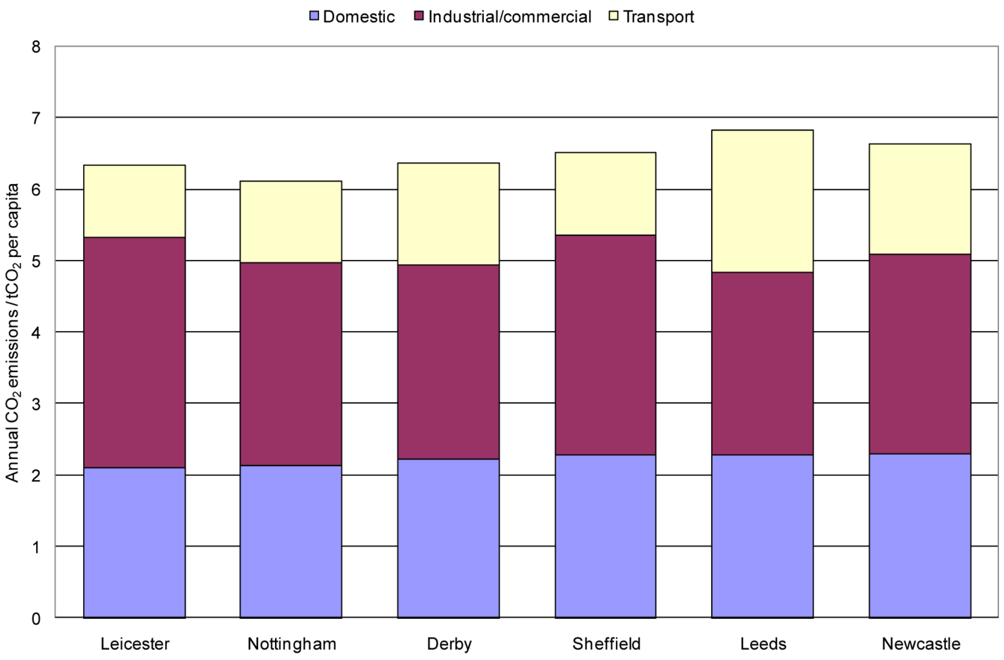

Figure 2: Comparison of per capita CO_2 emissions of Leicester and five other UK Cities derived from data published by the Department of Energy and Climate Change

comparable to those for other UK cities (Figure 2).

Whilst valuable, such aggregated data cannot answer questions that are key to urban carbon management, for instance:

- What effects will refurbishing homes have?
- Is home improvement more effective than traffic management?
- What contribution may other initiatives have (e.g., biological carbon sequestration, district heating schemes)?
- What provides greatest CO_2 reduction per £ spent?
- How would citizens react to each initiative?
- What would be the costs and benefits?
- The 4M project seeks to provide new insights that will help answer such questions.

Measuring and Modelling City Carbon Emissions

The 4M project, now in its second year, has focussed to date on measuring carbon emissions and stores across the city of Leicester, in order to enhance existing, and develop new, carbon models. The following sections describe the measurements made and the initial results from modelling.

The Living in Leicester survey

An ongoing investigation of a representative sample of Leicester households is key to understanding the relationships between household composition, socio-economic status, house type, and the energy used in homes and for travel. It also provides insights into the way people use and manage any outdoor space that maybe associated with their dwelling. The Living in Leicester survey has therefore provided a unifying focus to the measurement part of the project, and a consistent and comprehensive data set; the first such data set collected in the UK.

The face-to-face computerised questionnaire was administered at 575 homes (i.e. one in 50 Leicester homes), which were randomly selected after stratifying by percentage of detached homes and percentage with no dependent children in each of the 36 MLSOAs[1] in Leicester. The home questionnaire was devised by the 4M team and conducted on their behalf by NATCEN (the National Centre for Social Research). NATCEN's surveyors were trained with help from the 4M team and included individuals with Asian language skills (Leicester has a large Asian population)[6]. Additionally, two temperature loggers were left to record internal temperatures over a seven month period, initial gas and electricity meter readings were made at the time of interview with a final set of readings made by the 4M team after one year. More recently a detailed postal questionnaire of domestic appliance ownership and usage has been conducted, results of which have updated DECC's understanding of the patterns of appliance use. A detailed travel questionnaire is also planned.

Later in the 4M project, to probe the reasons for some of the relationships found in the survey, detailed face-to-face interviews will be conducted with approximately 50 the householders. Interviewers will present householders with their energy consumption data and the impact of travel patterns for that household. The interview will also explore knowledge of building energy conservation, willingness to invest in energy efficiency measures, implications of travel choices, and willingness to make changes to driver and travel behaviour. Results will shed light on the likely impact of the national FITs, RHI and PAYS schemes and feed into DaSTS strategy formulation.

Domestic buildings

The UK housing stock has been constructed, demolished and refitted over many centuries. Nationally, 64% of UK houses were built when no thermal standards for construction existed, including large areas of solid-wall terrace housing and post-war (1940s and 1950s) semi-detached estates. Today gas fired boilers provide central heating and hot water around 83% of homes and nearly all the rest have a combination of electric storage and fixed room heaters (BRE, 2006). In Leicester, the most frequent housing types are semi-detached dwellings (37% of the city's housing stock) and terraces (36%), which proliferate towards the city centre (Figure 3) along with flats (18%). In contrast, the detached houses are found primarily in the suburbs (10%), (ONS, 2010). Over the years many homes have been made more energy efficient by insulation and use of more modern boilers and controls.

A Community Domestic Energy Model (CDEM), (Firth et al, 2010) has been designed for predicting national carbon emissions in a previous project[7]. It is based on the steady-state energy model BREDEM-8, the Building Research Establishment Domestic Energy Model version 8 (Anderson et al, 2002) and predicts monthly space heating energy use and estimates the energy use for hot water heating, cooking, and for lights and appliances.

CDEM is designed around the assumption that English dwellings can be divided into distinct types with energy predictions made for each type rather than for each individual property: a technique that is well established in the UK for stock modelling. In CDEM, 47 archetypes, representing different geometries and ages of dwelling, are used. The number of dwellings of each geometry is derived from the last Census (ONS, 2010) and the English House Condition Survey (DCLG, 2007) enables the proportions with different heating systems,

Figure 3: Terraced housing, which is superficially easy to renovate and insulate is, in the detail, surprisingly complex, especially at the rear.

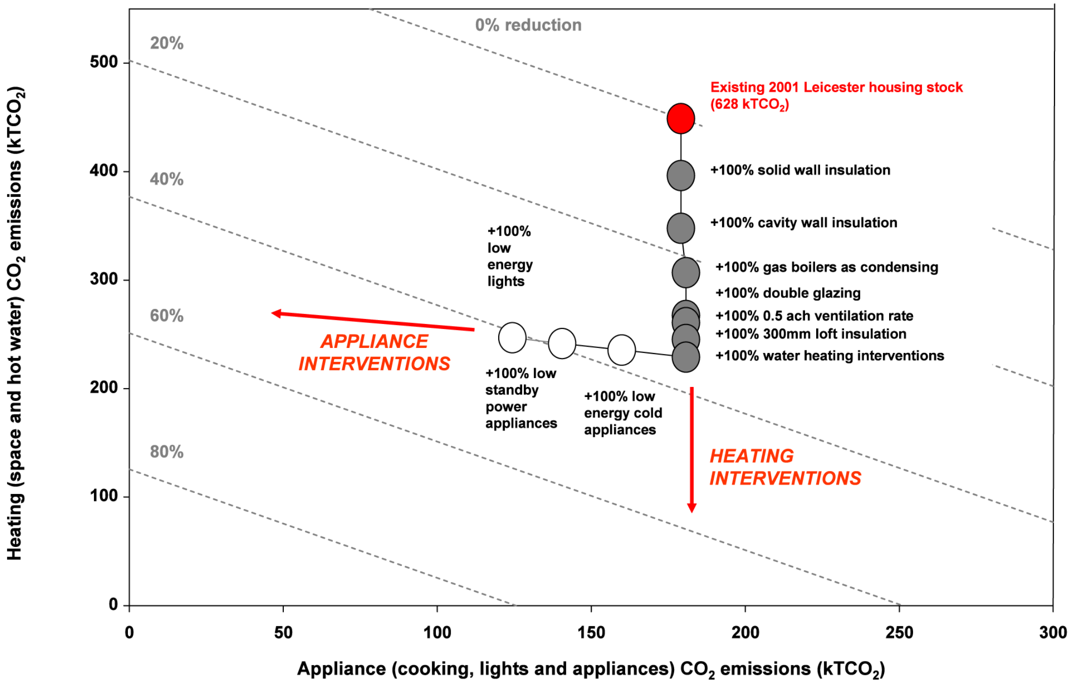

Figure 4: Predicted reductions in appliance and heating CO_2 emissions though refurbishment of the Leicester housing stock.

constructions (i.e. wall, roof and floor U-values), etc to be defined. The proportion with low energy lighting and the distribution of cooker types is provided by the Market Transformation Programme (MTP, 2007a; MTP, 2007b).

The CDEM model predicted that the 2001 Leicester housing stock of 115,752 homes had appliance CO_2 emissions of 628.0 kt CO_2 based on the 30 year average climate data, which is 5.4 t CO_2 per dwelling. This equates to 66 kg CO_2 per m² of dwelling floor area or 2.1 t CO_2 per person. Despite their greater exposed area, because they are newer and tend to be better insulated, detached dwelling had the lowest emission per unit floor area (62 kg CO_2 per m²) whilst end terraces had the highest (71 kg CO_2 per m²).

By separating out the total emissions for space heating and hot water, (primarily from burning gas), 449.0 kt CO_2, from the emissions for lighting, cooking and appliances (primarily electricity), 179.1 kt CO2, and plotting them, respectively, on the y- and x-axis of a graph, the impact of different energy efficiency measures can readily be seen (Figure 3). On this figure, the dashed lines show contours of equal emissions and the reductions in emissions due to the complete deployment of various energy efficiency measures (i.e. insulating the 99% of Leicester homes with solid walls that are not already insulated, and filling the 69% of wall cavities that are not filled).

The measure with the most potential to reduce CO2 emissions is to insulate solid walls; this would reduce emissions by 8% overall (Figure 4). By implementing all possible heating energy efficiency measures the overall heating CO_2 emissions are reduced to 230.8 kt CO_2 (i.e. by 35% of the total emissions). The combined effect of using low energy cold appliance, electrical items with low standby power and low energy lights, is to reduce appliance CO_2 emissions to 122.6 kt CO_2 (i.e. by 19% of the total), however the reduction in electricity consumption reduces internal heat gains and so the heating CO2 emissions increased slightly (from 230.8 kt CO_2 to 248.6 kt CO_2). Overall therefore, it is estimated that the combined effect of the heating and appliance measures would reduce the overall 2001 Leicester housing stock CO_2 emissions by around 41%.

The overriding messages from such modelling are that it is much more effective to focus on heating energy demand reduction than appliance energy demand reduction. But, even if all possible conventional energy efficiency measures are undertaken in every possible house the emissions reduction could not possibly approach 80%. Clearly, embedded new and renewable energy systems, district heating and other initiatives must also be adopted if deep cuts in emissions are to be achieved from the housing stock. Energy efficiency measures are likely to achieve much less in practice because many home owners will not invest - despite the incentive offered through PAYS. The follow-up household interviews seek to place a figure on the number of home owners that might take up such measures and also on the number that might adopt new and renewable energy systems.

Non-domestic buildings

Non-domestic buildings are, roughly speaking, all those that are not dwellings and so the range of sizes and shapes, construction types, occupancy patterns and heating, cooling, ventilating and lighting strategies is consequently very wide. Cinemas, hospitals, department stores, office blocks, corner shops, factories, supermarkets, workshops, schools, data centres and warehouses are all examples. This diversity makes it extremely difficult to develop robust models to predict the energy demands and thus the CO_2 emissions. Nevertheless, the 4M project is attempting to do this, and to do it in a way that will enable the many thousands of non-domestic buildings in Leicester to be analysed.

There are two main alternatives for modelling such large numbers of buildings. One option is to assign all buildings to a small set of distinct archetypes, based on their built form. These archetypes are then modelled in detail using dynamic thermal models that can predict the hourly energy demands and internal temperatures. The results are then combined in proportion to the Leicester's actual building stock composition to represent the overall behaviour at the city scale. The alternative approach is to model every building, however with this approach, dynamic thermal modelling is not feasible because the computing resource requirements would be excessive. With either option, knowledge about buildings' construction, energy systems and occupancy, is insufficient to justify the use of dynamic models.

These problems can be avoided by using simpler reduced-dataset models, which then enable each individual non-domestic buildings to be modelled. The model used in 4M is based on the European Standard BS EN ISO 13790:2008 (BSI, 2008) which is used in a range of models, including the UK's simplified building energy model (DCLG, 2008). It includes a representation of the building physics, albeit simplified, allowing the effect of changes in insulation, energy system, occupancy period etc to be explored. Although this approach reduces the quantity of data required about each building, the amount of information needed on the non-domestic stock of Leicester is still considerable, and its collection represents a major challenge.

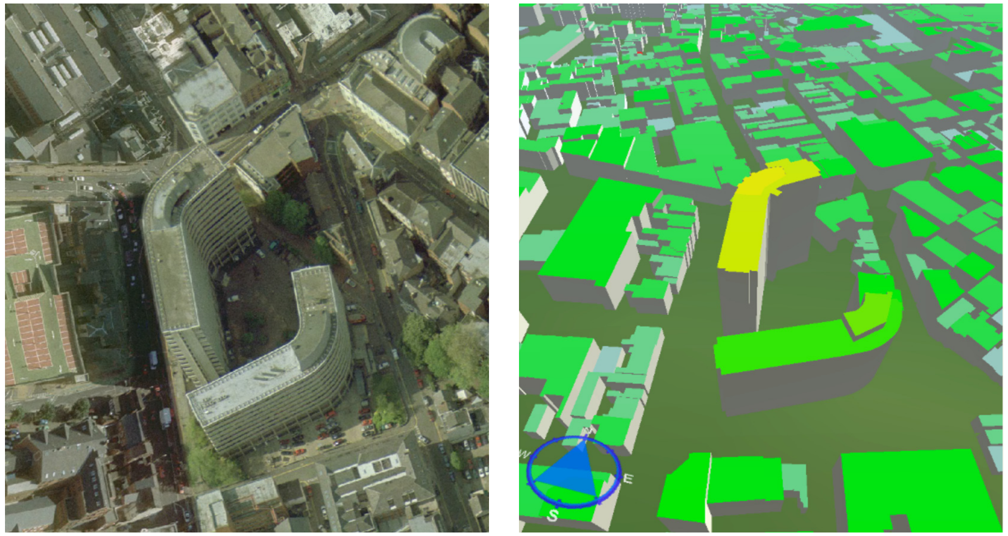

Figure 5: LIDAR-derived 2.5D building block model and corresponding image of building

It is well known (e.g. Mortimer et al, 2000a) that one of the fundamental determinants of energy use in non-domestic buildings is what they are used for. The business taxation database of the Valuation Office Agency (VOA) provides this information and the floor areas associated with that use. For this reason the VOA database is the most important source available. However, the VOA database deals not with *buildings* but with *premises* and the relationship between the two is complex. Buildings can contain single or multiple premises and premises can consist of parts of a building, a whole building, multiple buildings or a combination of multiple and part-buildings. What is needed is a way to relate premises and buildings that allows the modelling of buildings despite using premise-based data. This was achieved by using Leicester City Council's Local Land and Property Gazetteer (LLPG) which provides a link between premises and buildings. Analysis of the LLPG enabled the 4M team to produce an initial list of the non-domestic buildings in Leicester and the floor area given over to various activities.

The exposed wall area of each building, i.e. the area that is not touching an adjacent building, was estimated from a 2.5D model[8] of the city if Leicester (e.g. Figure 5) and from this the energy model can estimate the heat losses and gains and thus the energy necessary to heat and cool the building.

Detailed surveys of 340 premises in four cities, were undertaken between 1992 and 2002 (Mortimer et al, 2000b). These room-level surveys recorded the activity, floor area and the associated electrical equipment. Together with the period of room occupancy and the usage of the equipment and lights the energy demand profile per m^2 for each activity can be estimated. These data can then be used to generate the electrical energy demands and associated internal heat gains for lights and equipment.

Other required data pose even more formidable challenges. For example, the model requires a measure for each building's thermal mass, and sensitivity analysis shows that this has a significant impact on the results. In the absence of any direct methods of determining this parameter, which in any case is rather ill-defined, it may be necessary to combine a range of techniques such as surveys, historical mapping and written records.

The 4M non-domestic model, when completed, will allow the impact on CO$_2$ emissions of a range of interventions to be assessed, such as wall insulation, improved glazing and shading devices, more efficient electrical lighting, connection to a district heating system, and provision of local renewable energy generation.

Transport

Using the data from the transport section of the domestic household questionnaire, the CO$_2$ emissions generated by Leicester residents through travel for work, shopping, leisure and trips to take children to school can be estimated. The questionnaire focussed on journeys that began or ended at home - including multistage journeys such as home-school-work-shops-home; commuting on business to the airport, rail station etc. Raw data were collected on each household's vehicles (type, fuel use, engine size, age) and the monthly usage (frequency and occupancy) for different journey types. The journey types were split into four categories - very short (0-3 miles), short (3-8 miles), medium (8-50 miles) and long (50-100 miles). All journeys made were assumed to begin within the Leicester city boundary and through trips on the motorways were not included. The results produced an estimate for annual CO$_2$ emissions for such journeys of this type of around 0.6 t CO$_2$ per person, with trips of medium length, typically commuting to work, being responsible for 45% of these emissions.

The distribution of CO$_2$ emissions across the city has been estimated through the use of the Airviro Air Quality Management System (SHMI, 2009), combined with the latest emissions factors from the Department for Transport (Boulter et al, 2009). Traffic flows used in the estimation are obtained from a SATURN (Atkins, 2010) model of 3715 links within the city, combined with count data from approximately 952 sites.

The distribution of traffic, and therefore emissions, for 2005 represents the baseline against which traffic management scenarios will be tested, and is shown in Figure 6. Future work will compare the predictions from microsimulations with detailed road-side emissions measurements to improve estimates of the local scale emissions. This improved model, combined with air dispersion models, will enable the concentration of emissions and their variation with time across the city to be estimated more accurately.The study of transport emissions management focuses on the impact of road traffic schemes and green transport plans. A self-completed web-based questionnaire targeted at 30 schools and 30 places of work within the city will provide data to enable an estimate of the carbon emissions associated with regular travel to be estimated and the likely uptake of green travel plans[9] to be explored. Various traffic management schemes will also be explored and of particular interest are: shifting from private car usage in favour of walking; cycling and public transport; reduction of vehicle speeds; changes in vehicle fleet composition including increased use of electric and hybrid vehicles; and the integration of new Park and Ride services. By combining these data with those from the detailed household survey (see above), and by using the enhanced road transport models, the impact on the spatial distribution of emissions will be better understood.

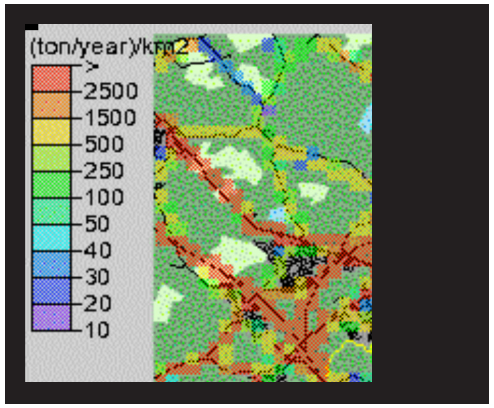

Figure 6: Distribution of annual CO2 emissions form Leicester road traffic as predicted by the Airviro programme suite (resolution 250mx250m squares)

Biological carbon storage and sequestration

Existing empirical data on biological urban carbon pools remains scarce, with inventories of trees restricted to public lands (Zipperer et al, 1997; Whitford et al, 2001) and estimates of soil carbon extrapolated from a small number of samples (e.g., Pouyat et al, 2006). Whilst this approach has generated a wealth of useful information, it does not fully account for the possible variation associated with different types of green space that occur in urban areas. At the current time, the paucity of such comprehensive information at a pertinent scale and resolution for urban landscape planning, policy-making and management is a major hurdle to our ability to understand, value and protect these above and below ground carbon pools. In the 4M project, a detailed investigation of the carbon stores associated with vegetation and soils was undertaken in different types of green space (herbaceous vegetation, shrubs, tall shrubs, trees, domestic gardens and allotments) across the city. This involved surveying over 2000 trees and taking soil cores from approximately 200 independent sites. Subsequently, these data have been used to generate and parameterise models that estimate urban carbon storage.

Figure 7: Soil sampling and subsequent laboratory analysis enables the carbon content of urban soils to be measured. There is a substantially higher concentration of black carbon, primarily from diesel-fuelled vehicles, close to main roads.

The significance of urban biological carbon stores is ultimately dependent on the management they receive. For example, the generation of carbon emissions arising from day-to-day management activities (e.g., through the use of lawn mowers, chainsaws, vehicles, chipping machines, fertilizer application) may even potentially negate any positive sequestration effects if they are not minimised. Information derived from Leicester City Council and the Living in Leicester household questionnaire will improve our understanding of such matters for both public and privately owned green spaces.

In the long-term, the carbon sequestered into vegetation will eventually be returned to the atmosphere when it dies or is destroyed, and replacement is therefore necessary to counterbalance the CO$_2$ released by decomposition (Nowak et al, 2002). Similarly, where possible, the decomposition of waste material should be limited via lasting carbon storage solutions (e.g. wood products) or the biomass used as an alternative renewable fuel source so that the release of CO$_2$ is accompanied by substitution for fossil fuel energy sources (Nowak et al, 2002; MacFarlane, 2009). In some instances, trees lost in urban areas will be replaced through natural regeneration, but the majority are likely to require active replanting in order to maintain current stores of carbon (Rowntree & Nowak, 1991). This is of particular importance on public land,

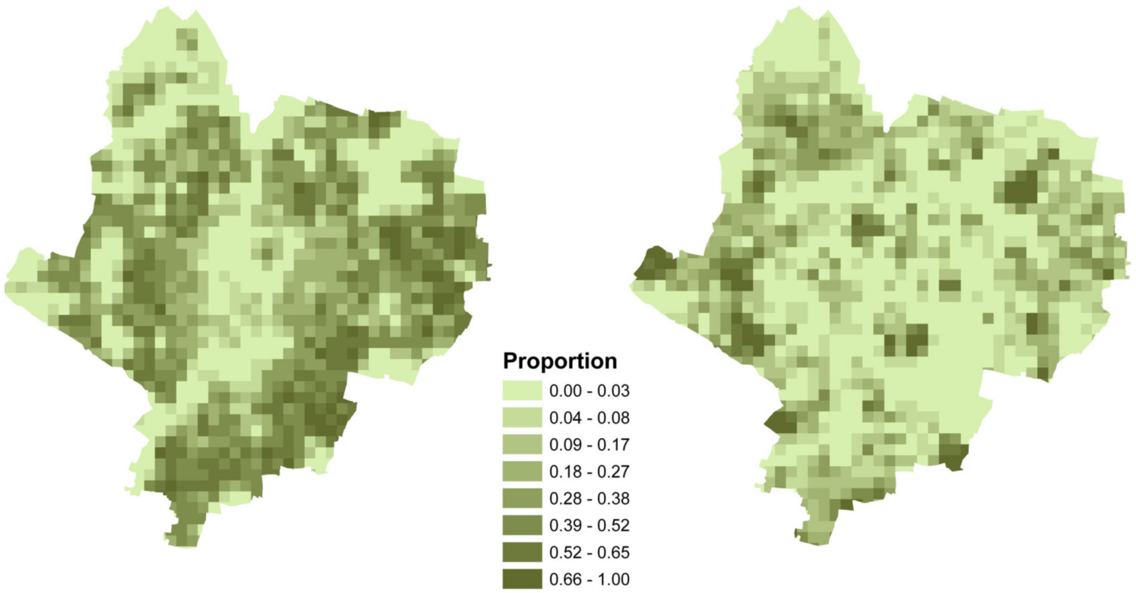

Figure 8: The distribution and proportion of (a) domestic gardens and (b) council managed land occurring across Leicester (resolution 250m x 250m squares)

where trees are frequently removed or subject to surgery in response to concerns about subsidence or human safety (London Assembly Environment Committee, 2007; Britt & Johnson, 2008). However, this issue cannot be addressed simply by top-down policies focused on land that is publicly controlled, as much of the urban landscape is privately owned. Bottom-up policy schemes encouraging householders to participate in strategies to augment urban biological carbon pools must therefore also be prioritised. In the UK this is particularly pressing due to increased infill development and the ‘garden grabbing’ phenomenon, as well as a growing trend to pave over front gardens to create off-road parking (RHS, 2007).

In order to facilitate the development of targeted policies that will maximise biological carbon storage through increased sequestration, above and below ground carbon pools are being mapped to assess how they vary in relation to land ownership (Figure 7). It is anticipated that policies to increase carbon storage within gardens, and other privately owned lands, will be seen as more creative and positive by the general public than many other approaches to mitigating emissions, such as energy from waste schemes and road use taxation.

The impact on below-ground carbon stores of capping formerly biological active soil with impervious surfaces is, as yet, unclear and has received little attention by researchers (Lorenz & Lal, 2009). Within urban areas, artificial surfaces (e.g., roads, pavements, hard standing, car parks, patios) make up a significant proportion of overall land cover. Indeed, in Leicester approximately 27% of land is capped in such a manner. The next phase of work has begun to address this issue and further refine soil carbon storage estimates.

Outcome and Conclusions

The 4M consortium have collected primary data and combined this with secondary data as a basis for understanding the carbon footprint of the UK city of Leicester. These data will assist the development of models describing domestic and non-domestic building energy demand, traffic emissions and biological carbon storage in vegetation and soils. Some initial observations can be made from the work undertaken so far.

Questionnaire surveys have provided *in situ* insight into household energy, travel and garden management behaviour through the involvement of individuals within their own homes. This has proved invaluable for development of an integrated dataset of information about three sectors that are typically studied separately. The next phase of analysis will seek to identify patterns across the participating households for use in follow-up interviews and inclusion in model development.

A community domestic energy model has indicated that refurbishment of the Leicester housing stock, could achieve a maximum reduction in household carbon emissions of about 41%. The model is being refined, and further data will be collected, so that the emissions cuts possible by individual households and the costs of achieving these can be calculated.

A non-domestic energy model capable of deployment at the city scale is being developed by integrating available diverse datasets. The model will be combined with digital mapping resources to realise a powerful support tool that will enable planning mechanisms to play an effective role managing carbon emissions from non-domestic buildings.

The calculation of carbon emissions associated with travel will extend current knowledge by estimating the carbon emissions associated with congestion. The enhanced models will allow the emissions reduction due to changes made by individual travellers to be established as well as the knock-on effects on other road users. Questionnaires will provide a better understanding of the trip characteristics of gross emitters and inform policy aimed at modifying travel behaviour.

The carbon stored in urban soils and vegetation is much greater than previously assumed. Indeed, on a per unit area basis, urban carbon pools are substantially larger than those associated with agricultural land. Future work will focus on determining how to enhance the capacity of urban areas to sequester carbon through further ‘greening’ of the environment and careful management of green spaces.

The findings from Leicester, and the data collection and modelling tools developed, will, when the project is complete, open up the possibility of measuring, modelling, mapping and managing the carbon emissions of other cities in the UK, Europe and beyond.

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Endnotes

1. The benefits that humans receive from ecosystems, such as the atmospheric, water & nutrient cycles and recreational opportunities.
2. DECC publishes regional and local authority fuel consumption figures for: electricity, gas, road transport, remaining fuels (coal, manufactured solid fuels, non-road transport petroleum and renewables) and total energy consumption (DECC, 2009a). Electricity and gas consumption data (domestic and non-domestic) are also available at middle layer super output area level (MLSOA, minimum population 5,000, approximately 2,000 households) and lower layer super output area level (LLSOA, minimum population 1,000, approximately 400 households) in England and Wales; as well as at intermediate geography zone level (IGZ, minimum population 4,000, approximately 2,000 households) in Scotland (DECC, 2010b). The gas and electricity consumption figures are based on sales figures estimated from metered consumption whereas road transport and other fuels are modelled by AEA Energy and Environment on behalf of DECC, using a number of data sources. Total fuel use is simply the aggregate of the others. At MLSOA and LLSOA there are some problems with misallocation (incorrect sector or incorrect geographical area) and issues of disclosure prevent proper allocation in commercially sensitive areas with significant consumers.
3. Electricity meters that record half-hourly energy use and relay the data to a central database. Feed-back to householders is possible, which can aid their understanding of the link between their activities and the resulting energy demand.
4. The Carbon trust has indicated that the carbon footprint of the UK's non-domestic buildings can be reduced by over a third by 2020 given appropriate strategies, including all feasible energy efficiency measures, improved lighting, and heating and lighting controls (Carbon Trust, 2009).
5. The data points bear no direct relationship to the households surveyed but preserve a sense of the number and rough location of those interviewed.
6. All the interviews were undertaken between 17/3/09 and 18/7/09 and each interview lasted about 45 minutes and had at least 247 questions supported by 51 show cards. There are 1411 anonymous and 157 confidential variables in the complete data set.
7. The 'Carbon Reduction in Buildings: a Socio-technical, Longitudinal Study of Carbon Use in Buildings' (CaRB) consortium of 5 universities sought to: improve the understanding of how people actually use energy in buildings; formalise this understanding in models that describe the current domestic and non-domestic building stock and the patterns of energy use; and produce tools to assist policy makers, consultants and others in their efforts to reduce national CO2 emissions (see Lomas 2010 and at http://www.carb.org.uk/).
8. The 2.5D model was created using LIDAR technology, in which a plane overflies the city so that a laser can rapidly scan the surface below. By analying the reflected light the relative heights of objects, such as trees and buildings, can be estimated. Combining this data with Ordnance Survey MasterMap data, enables the heights and exact perimeter position of buildings to be deduced and a 2.5D building block model produced.
9. Schemes such as ride sharing, using buses, minibus services, walking, providing safe routes to schools, provision of shower facilities, recycling of bicycles in schools, and providing loans for purchasing bicycles.

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