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## **URBAN DEVELOPMENT, FORM AND ENERGY USE IN BUILDINGS: A REVIEW FOR THE SOLUTIONS PROJECT <sup>1</sup>**

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### **1. Introduction**

In an age of global climate change and carbon emission reduction targets, the energy efficiency of urban development is a key factor in the sustainability of cities. Some aspects of the relationship between urban form and energy use have been well described. Newman and Kenworthy (1989), for example, demonstrated a curvilinear relationship between urban density and per capita energy use, through an analysis of a 32 cities world-wide. Cities characterised by high density development (e.g. Hong Kong and others in the far East) are the most efficient energy users, whilst low density cities, typified by those in North America and to a lesser extent Australia, are the least efficient. The differences are attributed to the role of transport, with low density cities typified by highly dispersed activities, making public transport difficult, and thus a high dependence on more energy intensive private transport.

Such studies, however, address only that portion of total urban energy use that relates to transport. Within the SOLUTIONS project, such transport energy demand can be assessed via the land use and transport interaction (LUTI) modelling to quantify trips by mode, plus a tactical transport model to assign these trips to a network, plus a further model, such as TEMMS (Namdeo *et al.*, 2002), in which a detailed characterisation of the vehicle fleet is made, addressing vehicle type, size, fuel etc, so as to arrive at an estimate of transport energy use. Our concern in this paper, therefore, is to address the implications of urban development and form in terms of its impact on non-transport energy use. Is this a significant issue, and if

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so what options are available for assessing the impact of the urban form options tested within SOLUTIONS, in terms of ‘building’ energy demand (which we could add to our transport energy forecasts to arrive at a total urban energy demand)? Are there practical options for assessing building energy using outputs of the ‘design based’ work packages – i.e. results of the LUTI modelling at the city scale, and/or the local design specifications at the neighbourhood scale? Table 1 summarises the design options to be tested within SOLUTIONS.

**Table 1.** SOLUTIONS design options for accommodating high growth

(a) Neighbourhood / Local scale

| <b>Design Type</b> | <b>Description</b>   |
|--------------------|--|
| Business as Usual  | <p>Development in ‘pods’ of different size and land use of main roads.</p> <ul style="list-style-type: none"> <li>▪ Mostly segregated land use (e.g. separate commercial parks)</li> <li>▪ Low density (20-40 dph)</li> <li>▪ Gated or estate type neighbourhood unit; Off line</li> <li>▪ Dispersed jobs and services</li> <li>▪ Tributary style street pattern at micro and meso scale</li> </ul>  |
| Neighbourhood unit | <p>Cells of 2-8,000 people, forming inward looking distinct enclaves</p> <ul style="list-style-type: none"> <li>▪ Partially mixed land use</li> <li>▪ Medium density (30-50dph)</li> <li>▪ Closed cell neighbourhood; Off line</li> <li>▪ Centralised jobs and services</li> <li>▪ Tributary street pattern at micro scale; grid/web at meso scale</li> </ul>  |
| Radical urbanist   | <p>Open cell units in pedestrian permeable clusters forming a township</p> <ul style="list-style-type: none"> <li>▪ Mixed land use</li> <li>▪ High density (40-70 dph)</li> <li>▪ Open cell neighbourhood; on line (astride)</li> <li>▪ Centralised jobs and services</li> <li>▪ Grid/web street pattern at micro and meso scales</li> </ul>   |
| High street        | <p>Public transport spine forms a focus for activity along a continuum; density falls away from spine to parallel green space.</p> <ul style="list-style-type: none"> <li>▪ Mixed land use</li> <li>▪ Medium, graded density (mean 30-50 dph, but wide range)</li> <li>▪ Continuous neighbourhood with on line township and edge on localities</li> <li>▪ Linear focus to jobs and services</li> <li>▪ Grid/web street pattern at meso scale; grid at micro scale</li> </ul> |

Source: Hugh Barton, SOLUTIONS paper on Local Design Archetypes, 12/8/04

(b) City / Strategic scale

| Design Type                           | Description   |
|---------------------------------------|---|
| Trend                                 | <ul style="list-style-type: none"><li>▪ Maintain greenbelt</li><li>▪ Prioritise development to 1. brownfield, 2. sub/urban with good public transport access, 3. other areas with good access, including those with high capacity transport corridors</li><li>▪ No pricing</li><li>▪ Public transport and highways investment</li></ul>                           |
| Compact city                          | <ul style="list-style-type: none"><li>▪ High density development and infilling, very high density around transport nodes and employment centres</li><li>▪ Relax green belt, open space and recreation constraints within urban footprint (except for SSSI etc).</li><li>▪ Area wide distance based road pricing</li><li>▪ Public transport improvements</li></ul> |
| Remove planning restrictions          | <ul style="list-style-type: none"><li>▪ Development permitted in all sites but those of highest environmental, scenic or cultural value</li><li>▪ No pricing (option to include pricing)</li><li>▪ Highway improvements</li></ul>   |
| Planned expansion and new settlements | <ul style="list-style-type: none"><li>▪ Relax greenbelt constraint in areas of high employment growth and good transport connections</li><li>▪ Minimum density and requirement for local employment</li><li>▪ Master planning for a cellular self contained settlement pattern</li><li>▪ No pricing</li><li>▪ Highway improvements</li></ul>                      |

Source: Tony Hargreaves, SOLUTIONS EC meeting, 27/6/05 (Strategic options for London)

## 2. Energy use in buildings

In the UK, buildings account for over half of all energy consumed (compared to 41% in the EU, and 36% in the USA), with less than 25% each for transport and industry (Steemers, 2003). Steemers (2003) notes that such national energy figures are likely to be conservative with regards to urban areas, as in cities there is likely to be proportionately less transport energy use due to better public transport, more walking, traffic congestion and limited parking – for example, in London, only 10% of commuters travel by car, compared to the national average of 40%. Commercial buildings are concentrated in cities, and have a greater energy demand per square meter than housing – an air conditioned office built to current building regulations uses six times the energy per unit floor space than a house. Note that whilst domestic carbon dioxide emissions have remained relatively stable over the last decade, this is as a result of a switch from coal to gas or nuclear supply; energy demand from housing increased 18% from 1990 to 2003 (DEFRA, 2005). Steemers notes that for London, the ratio of building stock energy use to transport energy use is approximately 2.2:1. This is based on

the analysis of Lewis (2000) who gives the London energy breakdown as buildings 72% (housing 35%, commercial 26%, industry 11%) and transport as 28% (cars 14%, goods vehicles 8%, air/rail/bus 6%). Steemers thus concludes that the energy and environmental implications of buildings are much more significant than that for transport, and that transport issues receive greater political attention as there is a stronger association of local pollution to cars; relatively rapid fleet turnover give greater opportunity for management intervention; and because cars are associated with other issues, such as accidents and social impacts.

### 3. Building energy use and urban form

The preceding analysis suggests that it is potentially appropriate to address energy use in buildings within the SOLUTIONS project, as this is such a significant share of total urban energy demand. However, SOLUTIONS does not seek to assess the sustainability implications of development *per se*, but rather the impact of the form of development, which we could characterise as the type of activity (land use), its location relative to other activities, and the density of development (which is manifest in different geometric forms in both two and three dimensions) (see also Table 2). Thus before attempting to assess energy demand from buildings, it is important to consider the extent to which energy use within the built stock is sensitive to urban form.

**Table 2.** Significant structural variables at different scales, affecting energy use.

| Structural variable                        | Region | Individual settlement | Neighbourhood | Building |
|--|--------|-----------------------|---------------|----------|
| Settlement pattern (e.g. size and spacing) | ✓      |                       |               |          |
| Communication network between settlements  | ✓      |                       |               |          |
| Size of settlement                         | ✓      | ✓                     |               |          |
| Shape of settlement (circular, linear etc) | ✓      | ✓                     |               |          |
| Communication network within settlement    | ✓      | ✓                     |               |          |
| Density                                    |        | ✓                     | ✓             |          |
| Interspersion of land uses                 |        | ✓                     | ✓             |          |
| Degree of facility centralisation          |        | ✓                     | ✓             |          |
| Layout (estates etc)                       |        |                       | ✓             |          |
| Orientation of buildings / building groups |        |                       | ✓             | ✓        |
| Siting relative to microclimate            |        |                       |               | ✓        |
| Design                                     |        |                       |               | ✓        |

Source: Owens, S (1986: p5)

In one of the earlier works on energy demand and land use Steadman (1979) discusses the energy implications of different forms of urban development, considering both density and form. He focuses on energy use in transport and commercial and residential buildings, assuming energy use in industry to be largely independent of urban form. With respect to density, he concluded that very high density living consistent with a Soleri Arcology style compact city would reduce travel energy demand, but would entail high building energy costs due to the added demand for lighting and cooling, High density living would also entail more energy intensive construction and limit the opportunity for solar energy supply. Conversely, low density living provides opportunities for energy efficient buildings with solar gain, but at the cost of high transport energy demand. This suggests the possibility of a density level at which total energy use (transport plus building) is at a minimum (although Steadman was not explicit on this point).

Steadman (1979) then considered, also from a theoretical perspective, the energy implications of different urban forms, based on the theoretical land forms first described by Lionel March. A key observation here is that settlements of the same density may have radically different forms. For example, high density development along linear routes, a grid pattern say, can have an identical density to development focussed on a central place. Steadman discussed the energy implications of such 'line' and 'blob' patterns. He noted that dense linear development along transport routes would be more energy efficient than compact central development, as buildings could be more energy efficient (a linear pattern better permits natural lighting and ventilation and passive solar gain; infrastructure can be shared. Local food production and return of organic waste to land would also be possible as all houses are in close proximity to undeveloped land). On these criteria, he concluded that high density linear development was the preferred form of urban growth as it maintains green land and access to more distant services, factors lost in low density wide-area suburbanisation. Steadman's analysis indicates that both the density and pattern of development materially affect energy demand.

More recent literature is inconclusive as to the relationship between building energy use and urban form. Some authors conclude that higher building densities reduce energy demand (e.g. Holden *et al*, 2004; Mindali *et al*, 2004) whilst others believe that increasing density can increase energy demand due to restrictions on natural ventilation and light, and opportunity for solar gain (e.g. Hui, 2001, and Larivière *et al*, 1999). In a review of the issues related to housing, Steemers (2003) concludes that energy arguments for and against densification of

cities is finely balanced, and will depend upon infrastructure issues (i.e. opportunities for buildings to share water and energy networks; CHP and district heating). However, as solar obstruction angles (a product of building height and separation) increase above about 30°, densification becomes unattractive from an energy efficiency perspective. For terrace or courtyard housing, this angle equates to about 200 dwellings per hectare (assuming 125m<sup>2</sup> per dwelling), well above current UK densities of c 25 dph, and PPG3 guidance of up to 50 dph. Thus Steemers concludes that high housing densities within the UK can be achieved without significant adverse energy implications.

Steemers (2003) describes three form factors that can be manipulated to increase density. Firstly, building depth can be increased (e.g. via a ground floor extension) and this increases heating demand and reduces natural light penetration, giving an estimated 5-10% energy demand increase for a two storey addition to a three storey terrace. Secondly, building height can be raised, or the space between buildings reduced. This increases obstruction angles and reduces passive solar gain, but as solar energy is a small fraction of heating in conventional houses, this only increases energy demand by between 6 and 15%. Conversely, apartments are 40% more efficient in heating terms than detached houses (so long as building depth is limited to 10-12m). For example, surveys by the Building Research Establishment (BRE) show that the average heat loss for a flat is 172 W/°C compared to 365 W/°C for a detached house (Shorrocks and Utley, 2003). Thus, a third form variable, ‘compactness’ is also influential in building energy efficiency. The importance of building form factors varies with the type of building – for example, space heating is the most significant use of energy in housing, but not in offices (Table 3).

**Table 3.** Energy use breakdown (%) for UK domestic and commercial buildings

|                       | Housing | Office – air conditioned | Office - Naturally ventilated |
|-----------------------|---------|--------------------------|-------------------------------|
| Space heating         | 60      | 22                       | 41                            |
| Water heating         | 23      |                          |                               |
| Lights and appliances | 10      | 34                       | 47                            |
| Fans/ pumps           |         | 30                       | 12                            |
| Refrigeration         |         | 14                       |                               |
| Cooking               | 7       |                          |                               |

Source: Steemers (2003)

With respect to offices, the primary energy demand is for lighting and, in the case of air conditioned offices, fans and refrigeration. The route to more energy efficient offices is thus designs that avoid (or reduce) the need for air conditioning and artificial lighting, rather than reducing heat losses, as is the case for the housing stock. This can be achieved by shallow plan (low depth) buildings, typically 12-15m, allowing natural lighting and ventilation. This suggests that energy efficient office developments must be less dense, but Steemers (2003) notes that this need not be the case, as avoiding air conditioning can save up to 30% of the building volume.

Hui, (2001) concluded that it is possible to have a high density urban area with a mix of high and low-rise buildings and a high degree of natural ventilation but did not quantify any relationships. Steemers (2003) calculates that, in the case of both naturally and mechanically ventilated offices, increasing density by increasing building depth will increase energy (thermal savings are more than offset by lighting and ventilation demands). Natural ventilation can typically save 40% of the energy demand of air conditioning, and building design strategies are available to obviate the need for air conditioning. However, urban noise and air pollution are frequently cited as important reasons for installing air conditioning, and Steemers (2003) argues that this traffic related issues needs to be addressed before the full advantages of such office designs can be realised. The alternative densification strategy is to increase building height (or reduce building spacing), which Steemers (2003) calculates will increase energy demand by 23% (for air conditioned offices) and 45% (non- air conditioned offices) for an obstruction angle of 30°.

#### **4. Estimating building energy use**

From the preceding discussion, and other literature, we can list the factors that influence the demand for energy in buildings as:

- Type of activity (e.g. housing, commercial, industrial) and the occupant behaviour;
- Design factors related to urban geometry – e.g. obstruction angle (a product of height and plan depth/spacing to adjacent buildings), opportunity for passive solar gain;
- Design factors related to buildings morphology – e.g. extent of glazing, orientation;
- Thermal properties of construction materials – relative amounts and U-values of materials used, embodied energy of material;

- Efficiency of internal systems – e.g. heating and lighting systems, air conditioning use in offices (itself affected by external environmental quality);
- Opportunity for energy efficient sharing of infrastructure (e.g. water or energy networks);
- Internal and external temperatures;
- Fuel price –affects consumption and fuel switching.

This is not an exhaustive or prioritised list, but does serve to illustrate that the range of variables that determine energy use in urban buildings is extensive. This suggests that multivariate modelling could be an appropriate means of assessing urban energy demands under alternative development scenarios. However, Nijkamp and Perrels (1994) note that whilst energy impact methods and models are essential for energy resource analysis there are relatively few such tools available due to a lack of appropriate databases and behavioural analyses. Furthermore, with respect to the relative importance of some of the factors listed above that affect building stock energy performance, Ratti *et al.*, (2005) (citing Baker and Steemers, 1992), note that whilst building design accounts for, on average, 2.5 x variation in energy performance, and system design and occupant behaviour account for 2 x each, little is known about the role of urban form and geometry in building stock energy performance.

Table 4 summarises Nijkamp and Perrels' 1994 review of methods for local and regional energy analysis focused on methods for forecasting energy demand and for understanding the implications of alternative energy technologies. In this review, the models discussed operate largely at the regional scale, and appear to have little ability to assess the energy implications of urban form. Those models with a spatial component in which households, commerce and industry are represented have been developed for application at the national scale. Nijkamp and Perrels (1994) describe the MEDEE model and note that this can be applied at the city region scale, so long as the several hundred variables within the model are underpinned by an appropriate database. In practice, this proves difficult and many data assumptions need to be made. Masahiro and Sakamoto (2005) describe a cartographic analysis in which the Tokyo thermal environment (urban heat island) is attributed to a range of urban form characteristics. Form factors deemed associated with elevated external temperatures included area devoted to roads and buildings, building density and surface area, prevalence of medium and high rise buildings, complexity of urban morphology, and prevalence of fire resistant buildings and concrete surfaces. The study illustrates that urban form is a factor in the energy budget of the building stock, but is not of direct use in assessing the impact of form on energy demand.

**Table 4.** Summary of local-regional energy models from Nijkamp and Perrels (1994)

| Approach                                     | Comments  |
|--|---|
| Input-Output models                          | Fixed coefficients relate production to energy use (e.g. energy use is related to GDP). Models tend to be regional in scale, are inflexible, require large databases and tend to be incomplete. Renewed interest via life cycle analysis approach. Applications are product focussed, and urban form is not considered.                         |
| Energy-environment models                    | Depict complex interaction between energy production (or use) and environmental implications, such as noise, air quality and climate change. Many examples, but most are large scale and urban examples do not consider urban form.   |
| Energy models with substitution              | These (mostly econometric) models express relationships between economic variables (capital, labour, energy and materials) and energy demand. They lack time series data, have an inflexible structure, and low relevance to energy supply planning. No urban form capability.  |
| Comprehensive regional energy systems models | Contain activity, socio-economic, financial, energy, and environmental modules, possibly with spatial representation. May mix several approaches (econometric, I-O, mathematical programming). Examples quoted here are regional (e.g. IIASA regional energy model used in a 1979 EU study), not urban in scale, with no urban form capability. |
| Energy circuit models                        | Developed to represent energy flows in ecosystems, and applied in urban and regional energy analysis to judge energy efficiency. Approach is based on ecological accounting to trace energy flows, which are assumed to determine regional function and structure.  |
| Cartographic energy-env. analysis            | Explicit spatial analysis in which detailed heat maps are produced of energy supply and demand of residential and industrial activities. Used to identify agglomeration advantages from district heating, integrated supply systems.  |
| Regional energy scenario analysis            | Scenarios are assessed in energy terms for broad, limited sets of potential future developments. Tend not to reflect regional inputs, but national or international policy (e.g. change in oil supply, national energy tax). May make use of other types of energy model.   |
| Multiple dimension energy policy models      | Energy policy is analysed by assessing discrete alternatives (e.g. using a MCA method), or continuously using large scale, integrated multi-sector I-O models.  |

## 5. Modelling building energy use at the urban scale

Whilst some of the modelling approaches in Table 4 are in principle relevant to the building stock energy prediction problem, no extant models appear available in which urban building stock energy use can be predicted with an explicit consideration of urban form. However, since Nijkamp and Perrels' review, a further class of models have been developed to assess

energy consumption within the building stock (including UK specific applications). In contrast to most of the models in Nijkamp and Perrels' review, which tend to be 'top down' models, these models are physically based, and are derived from architectural and engineering perspectives. They are built from 'the bottom up', that is, energy use predictions are based on a detailed characterisation of the building stock in the geographical area of interest. The two modelling approaches are complementary, as the 'top down' models can be used to assess, for example, the impact of fiscal policy using an econometric model, whilst conversely the physical models can be used to assess the impact of physical measures, such as a policies encouraging insulation, or (in principle) changes in physical form, the issue of interest here.

The Steemers (2003) assessment of building geometry (plan depth, height etc) impact on energy consumption described above, was undertaken using one such technique, known as the 'LT method' (lighting and thermal) (Baker and Steemers, 2000), a manual design tool developed at the Martin Centre, Cambridge, on behalf of the BRE. The LT Method (initially developed as a spreadsheet model, now available as a bespoke PC model) estimates the combined energy usage of lighting, heating, cooling and ventilation systems, based on over 30 design variables, to enable a building designer to make comparisons between design options at an early stage. Whilst the model is used to assess the energy implications of different designs for a single building, it has been used (Steemers, 2003) in conjunction with computer based imagery (a digital elevation model and remotely sensed images of the urban fabric) to determine energy consumption for 'large urban areas' (400 x 400 m). The technique has been used to explore urban form – energy relationships, given assumptions about the more detailed characteristics of buildings (U-values, glazing ratios etc). After a survey of part of London, standardised values were selected for these characteristics, and the technique applied to identify the energy implications of changing urban density. Steemers (2003) shows that, for naturally ventilated offices, doubling the density (by doubling height) typically increases energy consumption for the whole urban area under study by 25% (assuming density, as plot ratio, is within the range 1.25 to 5).

Ratti *et al.*, (2005) also explored the relationships between urban geometry and energy consumption using the LT method with default values for non-form variables. The 'geometric variables' that were manipulated were distance from the façade (passive/non-passive condition); façade orientation; urban horizon angle; and obstruction sky view. The relationship between urban geometry and energy consumption was explored for parts (250 x

250m) of London, Toulouse and Berlin (Mediaeval, Georgian and Modern layouts respectively). This required the derivation of a 3-D digital elevation model (DEM) from remotely sensed data, followed by image processing to provide the necessary geometric input data to the LT model, and thus estimate energy use.

The study demonstrated that DEM data could be used in conjunction with a building energy model to quickly arrive at an estimate of building energy use for an urban area. It also demonstrated the extent to which urban energy use is sensitive to urban geometry: for the three forms studied (all other factors, included climate were constant) the variation in energy use was 10%. This is small when compared to the effect of systems efficiency or occupant behaviour, but Ratti *et al.*, (2005) point out that (a) only three forms were studied; and that (b) a variation of 10% in building energy use could have tremendous impact on the energy budget of cities, and deserves careful thought in urban planning.

A second model which also takes individual buildings as the starting point in energy analysis is EEP (Jones *et al.*, 2001), the energy and environment prediction model, developed under the EPSRC Sustainable Cities programme by Phil Jones at the School of Architecture, University of Wales. EEP is designed to assist planners in making comparisons between energy efficiency measures (e.g. double glazing, installing condensing boilers, improving U-values of walls etc) for a group of buildings or urban area. The domestic energy module is based on the UK standardises assessment procedure (SAP) which gives an energy efficiency rating for a building based on data describing a buildings fabric, glazing, ventilation, water and space heating and fuel costs. EEP permits an area, rather than building scale assessment by allocating buildings to clusters that have similar SAP ratings, based on five building characteristics (heated ground floor area, façade, window to wall ratio, exposed end area, age). ‘SAP clusters’ are then assigned to one of a hundred types of building (20 building types x 5 age classes). To assess domestic energy use for an area, the buildings in the area must be assigned to one of the 100 building classes (by ‘drive by’ survey). The model is applied to determine the relative impact of different energy efficiency measures.

To determine total building energy use, EEP adds non-domestic building energy use to the domestic determinations using results of a DETR survey of non-domestic building energy use in which uses are split into 13 building types with a total of 48 sub-groups (e.g. a small hotel

uses 240-300 KWh/m<sup>2</sup>). To apply this function in EEP, properties must be identified from local authority building valuation databases or site visits.

EEP is capable of providing comparisons of the efficacy of alternative energy efficiency measures for large urban areas. However, with respect to the SOLUTIONS project, there are two obvious drawbacks. Firstly, urban form is not assessed explicitly, but rather form is addressed as a consequence of the building class (type: end terrace, semi-detached etc; and age). This means that SOLUTIONS designs would need to be expressed in a form compatible with EEP (using the 100 building classes). Whilst this is, in principle, possible at the neighbourhood scale, it is problematic at the city scale where the options tested are only realised within the land use transport model as zonal changes in density and floor space. Secondly, the survey element of EEP makes it labour intensive to apply – the first full application was to Neath Port Talbot, where addressing 60,000 domestic and 4,000 non-domestic properties was estimated to take 15 person months of data collection and input.

## **6. Land use transport modelling and buildings energy use**

The physically based approach to building energy assessment has been developed in recent years, through models such as EEP, so that with statistical generalisations, they may be applied to address energy use at a scale wider than individual buildings. However, current models are labour intensive to apply, and appear to offer few opportunities for assessing the energy implications of city scale designs tested using strategic land use models. A review of the energy consumption with respect to LUTI models revealed that there is currently a very limited capacity for using such models in building energy assessment, with few practical applications. A detailed review of the interactions between land use, transport and environment issues by the US EPA (EPA, 2001) discussed energy only in terms of energy use for transport. A further EPA review, in this case of 22 leading land use and transport interaction models, reveals that the assessment of building energy use was considered in, at most four of the models (Table 5).

From the models listed in Table 5, it would appear that building energy is assessed principally by using the LUTI model to forecast changes in land use, and energy use is then estimated by applying energy use coefficients specific to the land use variables. These coefficients need to be derived for the application area, so that they are appropriate to the land use variables (e.g. US and UK detached housing presumably have very different energy use characteristics).

**Table 5.** Land Use – Transport Interaction models with building energy assessment capability

| Model              | Model type and developer   | Buildings energy assessment capability   |
|--------------------|--|--|
| SMART growth index | Sketch planning model from Criterion planners, Portland Oregon.<br>www.crit.com  | Residential energy consumption. Requires housing numbers and type as input – energy probably assessed via use coefficient per household type and modelled change in housing stock  |
| SMART PLACES       | Sketch planning tool. ESRI GIS extension from Electric Power Research Institute, Palo Alto, CA.<br>www.smartplaces.com | GIS based tool with unsophisticated modelling. Energy is included as an output, but not clear if this relates to buildings, or how it is assessed.   |
| TRANUS             | Sophisticated market based model from Modellistica, Caracas, Venezuela.<br>www.modellistica.com/tranus                 | Provides inputs (e.g. land use by activity type) to other models (CUFM, Burden etc) for the calculation of environmental indicators, including energy consumption and emissions from buildings.  |
| UGrow              | Systems dynamics model from Wilson Orr, Prescott college, Arizona. www.prescott.edu                                    | Systems dynamics model with outputs that can be represented spatially using a GIS. Calculates energy use in response to specified policy options – spatial input capability; energy output uncertain. Land use- energy relationships would be specific to US development site. |

Source: Based on EPA (2000)

The Table 5 LUTI models are mostly simple sketch planning models with a simple, internal, building energy assessment capability. The exception is TRANUS, a sophisticated LUTI interaction model, similar to MEPLAN (the model and its derivatives used in SOLUTIONS), with a more resolved output of land use characteristics, that would appear to have the capability to interface with more resolved energy assessment models. In a review of building energy use and urban form, we could find only one study in which a LUTI model had been used to assess the impact of urban form on total (domestic plus non-domestic) building stock energy use. This study (Steadman *et al.*, 1998; Brown 1998) applied the TRANUS model to Swindon, UK, to assess the impact on transport, land use and energy use of four urban development scenarios – ‘containment and increased density’ (compaction), ‘high density dispersal’ (satellite developments), ‘limited peripheral expansion’ (edge development), and ‘trend’ (free market).

The Swindon study represents a continuation of the earlier studies of Rickaby (1987, 1991) in which alternative settlement patterns were assessed, but in which consideration of energy was

limited to transport and housing. Housing energy use appears to have been modelled using a statistical description of the residential building stock (type, age, built form, heating system), derived from the Census, DETRs regular English House Condition Surveys, and other sources (Bruhns *et al.*, 2000). The Swindon study represented a development over Rickaby's earlier work, in that: (a) land use and transport policies were assessed in combination; (b) the study was of an actual, not hypothetical, city; and (c) energy predictions were extended to encompass all the built stock, made possible by improved statistical data on the non-domestic building stock in Swindon.

TRANUS is a random utility model with an input-output formulation for the land use sub-model. The model starts from a description of the level and spatial distribution of basic industry (those that supply goods and services). An increase in industrial employment causes growth in local service industries, and growth in the demand for industrial, commercial and residential floor space. The model takes into account this demand, and the supply of available land and its relative accessibility, so as to predict where new activities will be located. The relative locations of different activities (housing, industry, commerce) are then used to estimate the demand for trips, which are then assigned to the transport network. This modifies the relative accessibility and hence affects the demand for land on subsequent iterations

In the Swindon TRANUS application, detailed data on buildings was available that “made it possible to test a unique representation of the floor space market, disaggregated into different building types” (Steadman *et al.*, 1998). Previous studies had been limited to an assessment of building energy use from the residential sector, due to a lack of comprehensive statistical data on the physical characteristics of non-domestic buildings. Details of the non-domestic building stock in Swindon came from a Valuation Office database, and a 1989 city building survey, so as to give a full picture of the numbers and types of non-domestic buildings, including their floor areas, activities, geometrical form and construction. This provided the basis for a new sub-model within TRANUS which simulates the market for domestic and non-domestic property, and which represents the building stock explicitly in terms of built forms and activity. This floor space model allows buildings to switch between domestic and non-domestic use, and is used to provide an assessment of the effect of changing density and land use mix on the built environment, including energy use within the total built stock (Steadman 1996; Steadman *et al.*, 1998).

## 7. The non-domestic building stock database

Non-domestic energy assessment within the Swindon study relied upon the availability of adequate data describing the local building stock (drawn from a valuation office database) and the energy use characteristics of buildings within that stock (derived via a bespoke survey). This database has since been further developed in the national non-domestic building stock (NDBS) project ([www.ucl.ac.uk](http://www.ucl.ac.uk)). The project, which is ongoing, has developed a database which contains information on approximately two million commercial, industrial and public sector buildings, and which has been used in to construct a national non-domestic energy and emissions model.

The NDBS database is constructed from: (a) Inland Revenue Valuation Office Agency data which provides descriptive data (including floor area, activity, floor levels, wall and roof material, heating and air conditioning systems) on 1.7 million non-domestic properties; (b) detailed (use, age, history, construction geometries, fabric) surveys of 3350 non-domestic buildings in four English towns (Manchester, Swindon, Tamworth, Bury St Edmunds); and (c) other sources of information on activity and floor areas (Yellow pages, census etc). By combing the data sets, it has been possible to make infer a detailed characterisation of the non-domestic building stock at the national level (Bruhns *et al.*, 2000).

One of the original motivations for developing the NDBS database was to support assessment of alternative policies for energy conservation and emission reduction. Therefore the surveys of the 3350 properties described above were designed so that information was collected not just about the building itself (see above), but also (for a sub-sample of buildings) the building service systems (heating, cooling, ventilation), room details (use, geometries), power consuming equipment, and records of energy consumption. These data have been analysed in several ways, including the calculation of specific energy use; that is GJ m<sup>2</sup> yr for different activities. There are 51 activities in the NDBS database, in nine major classes. Mortimer *et al.*, (2000) describe the derivation of specific energy uses for 34 of the most common activities, based on an analysis of 319 buildings in the NDBS energy survey. Elsayed *et al.*, (2002) provide more recent figures, based on a large (800) sample of buildings.

The NDBS database is still under development to establish new applications (e.g. establishing better relationships between employment and floor space), but several energy use applications have already been made. In addition to the Swindon-TRANUS study described above, these

include: current and future energy use predictions for Leicester, Milton Keynes and part of Barcelona using the Open University Dynamic Regional Energy Analysis Model (DREAM) (Titheridge *et al.*, 1996); and in ‘preliminary’ national level work on non-domestic building energy use and potential carbon emission savings (Mortimer *et al.*, 1998; Pout *et al.*, 2000) using the BRE Non-Domestic Energy and Emissions Model (N-DEEM). This model essentially links national floor areas for 75 activity types (from the NDBS activity database) to figures for specific energy use (Gj m<sup>2</sup> yr) disaggregated by four fuel types and 19 applications, from the energy surveys conducted in the four English towns. These bottom up estimates of total fuel use are calibrated to national totals and published in the *Digest of UK energy statistics*.

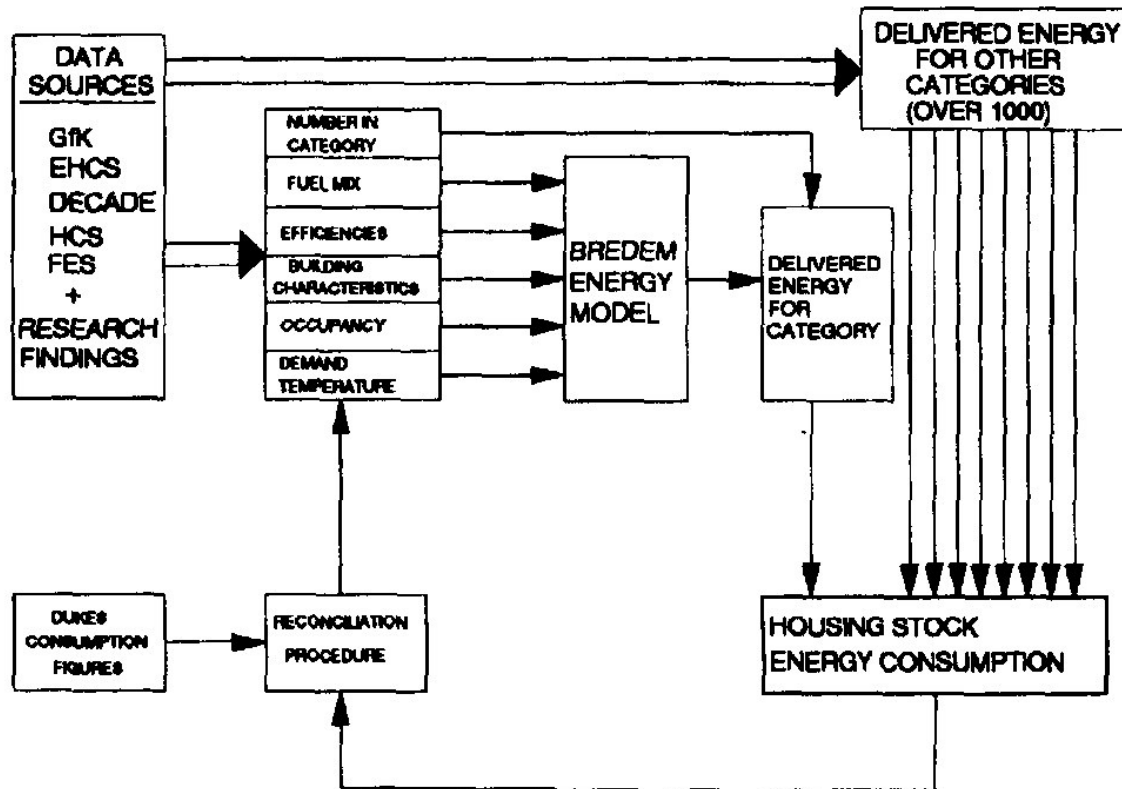
## **8. Domestic Building Energy Assessment**

Mortimer *et al.*, (1999) assert that energy use in the UK domestic building stock, and subsequent CO<sub>2</sub> emissions, are relatively well understood, referencing work done at the BRE (Shorrock *et al.*, 1992). This work includes the development of the model BREHOMES (HOusing Model for Energy Studies), a physically based model that has been widely accepted as a valuable policy tool. The structure of BREHOMES is described by Shorrock and Dunster (1997), and is shown in Figure 1. At the centre of BREHOMES is BREDEM (BRE Domestic Energy Model), a simplified physical model of energy use in individual dwellings that allows behavioural factors to be considered. BREDEM requires data on building elements (walls, doors, windows etc), their thermal characteristics (U-values), heating systems, internal and external temperatures, number of occupants and solar gains.

Shorrock and Dunster (1997) note that applying such a disaggregate model at the national scale requires a large amount of data, but that all the essential data does exist for the UK (e.g. floor area data from the English House Condition Survey, heating system data from market surveys etc). In BREHOMES, BREDEM is applied in conjunction with external data sources to assess typical energy demand for over 1000 categories of dwelling. National demand is then calculated as the product of these values and the number of dwellings in each particular category. BREHOMES is described as more than a model, as it contains a physical model (BREDEM), supported by a series of databases and a wider assessment process. The large number of dwelling types with BREHOMES is presumably a factor of the large number of variables within BREDEM. Many of these do not relate to physical form, and hence

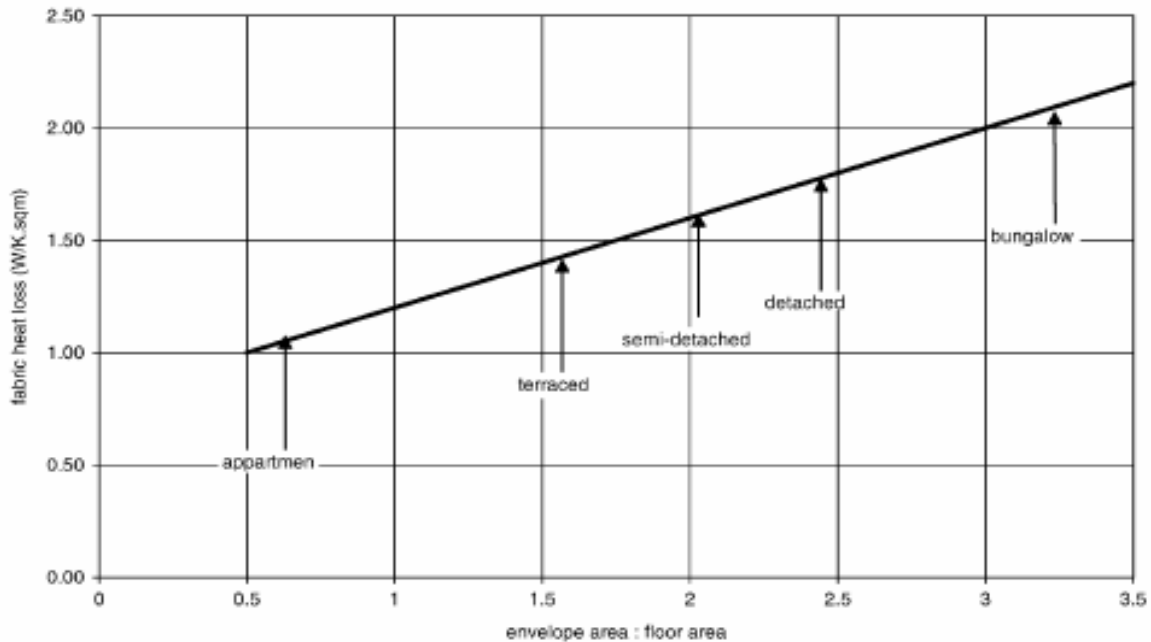
presumably could be held constant so as to develop typical specific energy use coefficients for a smaller set of dwelling types (terrace, flat, detached house etc).

**Figure 1.** The BREHOMES model of housing stock energy use (Shorrock and Dunster, 1997)



In a feasibility study of reducing CO<sub>2</sub> emission from UK housing by 60%, Johnston *et al.*, (2005), use a modified version of BREHOMES (Johnston, 2003) in which there are only two dwelling categories (pre- and post-1996), rather than in excess of 1000 as is usual in BREHOMES. This is interesting because first, it indicates that it is considered acceptable to aggregate dwelling categories to suit a particular application, and second because they justify their simplification (in part) on the grounds that, at the level of the whole building stock, the impact of dwelling type on energy use is small in comparison with the thermal performance of the construction materials and energy using systems. Nevertheless Figure 2 indicates that least heat loss per unit area varies by a factor of two between low density (bungalow) and high density (apartment) buildings. Given that space heating comprises about 60% of domestic energy demand, it must be assumed that building form is also significant with respect to energy demand. Murakami and Sakamoto's (2005) study (4 above), shows that heat loss (and hence energy demand) is also related to urban form for commercial buildings.

**Figure 2.** Relationship between building form and heat loss



Source: Steemers (2003) citing Martin and March (1972)

## 9. The significance of urban form to building stock energy demand

The context of this paper is a forthcoming assessment of alternative urban designs, realised at both city and neighbourhood scales, with respect to urban sustainability. The paper addresses urban energy use, a key assessment metric, and particularly that within the building stock, as transport related energy is addressed elsewhere within the SOLUTIONS project. The review has sought to establish the relative importance of building energy use and the sensitivity of building energy use to urban form, and also to identify possible tools and methods than could be used to assess built stick energy use for the SOLUTIONS urban designs.

Firstly, it is clear that the buildings are very significant users of energy, nationally consuming over half the total energy consumed. In the urban environment, they account for an even greater share of energy use (an estimated 72% in London, split roughly 50:50 between residential and non-residential use) as there is proportionately less private vehicle use here than at the national level. Any urban development, whether for residential, commercial or industrial uses, will thus have a major impact on the energy demand of a city.

SOLUTIONS seeks to test alternative urban designs at both city and neighbourhood scale. At the city scale, it is clear that any new development, in what ever form it takes (densification, new town etc) will substantively add to the energy demand from the building stock. However, if design options are to be tested against a ‘business as usual’ reference scenario, as opposed to a ‘no development’ scenario, then the differences between city scale design options may be rather small. The question is then, to what extent is energy demand sensitive to the built form characteristics (which we earlier tentatively defined as type of activity, its location relative to other activities, and the density of development, manifest in both 2D and 3-D) of the different city scale designs, rather than simply the level of development?

Steadman (1979) argued from a theoretical perspective, that the form of development was a significant factor in building stock energy use. However, of the main factors affecting building energy performance; urban geometry, building design, systems efficiency and occupant behaviour, the relationship between urban geometry and energy use is the least understood. Ratti *et al.*, (2005) provide one of the few empirical analyses on the relationship between form and energy use. For three 16ha urban forms (Mediaeval London, Georgian Toulouse, Modern Berlin), characterised using 3-D imaging, they applied the LT method, and found that energy use varied by an order of 10% between the forms (which they believe could be conservative). If this variation is applied to the total urban energy demand, then urban form is seen to be a very significant determinant on total energy use, more so that that for an exemplar transport policy, used here as a crude comparator (Table 6).

**Table 6.** Sensitivity of total urban energy use to urban ‘design’ options

| Sector    | Share (%) of total urban energy use <sup>a</sup> | Variation (%) in energy use due to factor of... | Variation (%) in total urban energy use due to factor |
|-----------|--|---|---|
| Buildings | 72   | Urban form <sup>b</sup> = 10                    | 7.2   |
| Transport | 28   | Road pricing <sup>c</sup> = 10                  | 2.8   |

a – Figures for London quoted in Steemers *et al.*, (2005). Transport figure includes air travel.

b – Figure from Ratti *et al.*, (2005)

c – Figure from Mitchell *et al.*, (2003) (an average from four Leeds road pricing schemes each with a £3 charge).

This crude example illustrates that energy savings achieved through urban design can be much greater than that from transport management. Note also that the energy demand from the building stock is also much more fixed than that of transport, due to a much slower renewal rate of buildings when compared to vehicles. Furthermore, the above example, only addresses the energy implications arising from alternative built geometries, and ignores other factors, such as the type of activity (residential, commercial etc) whose distribution may vary between city scale design options (and within a design option over time). Thus it is suggested that the SOLUTIONS project should seek to understand the impact of urban design options on the energy use in the built stock, if practicable.

#### **10. Assessing building stock energy use within SOLUTIONS**

Having determined that energy use in the urban built stock is very significant and is also sensitive to urban form, the next step is to determine if any building stock energy assessment techniques are available that could be applied within SOLUTIONS. The review of city and regional models from Nijkamp and Perrels (1994) suggests a lack of energy use prediction models capable of handling urban form. The more recent 'bottom up' models have a much greater ability to map energy use at fine spatial scale (e.g. EEP), but here too, there is little sensitivity to urban form (rather than building morphology). Ratti *et al.* (2005) note that, whilst many models have been developed in recent years to study and simulate urban energy consumption, such models are developed from the perspective of the building designer, and neglect important phenomena that occur at the urban scale: "In particular, the effect of urban geometry on energy consumption still remains understudied and controversial" (p762).

The relative lack of building stock energy assessment models is indicated by the Carbon Visions Buildings Project, a new EPSRC funded initiative, that seeks to develop computer models for predicting energy use in buildings at the national, regional, city and community scale (some £4 million appears to have been allocated to modelling, [www.carb.org.uk](http://www.carb.org.uk)). The aim is to use the models to forecast the impact of energy efficiency measures, renewable energy technologies, and socio-technical interventions on carbon emissions, but there is no indication that the 'urban geometry gap' identified by Ratti *et al.*, will be addressed.

There appears then, to be two basic options for building stock energy assessment within SOLUTIONS. One in which energy use is determined as a product of an activity description and associated specific energy use coefficient, the second in which energy use is determined

using the LT method, which requires a geometric description of the buildings in question. In principle, both methods are applicable at any scale, however, given data limitations, the ‘activity-energy coefficient’ method is suited to the whole city scale (SOLUTIONS strategic design options) and the ‘LT method’ to the neighbourhood scale (SOLUTIONS local design options). The implications of applying these methods within SOLUTIONS are described further below.

### ***10.1 Activity-energy coefficient method***

In this method, building stock energy use is calculated as a function of activity type, floor space, and specific energy use coefficients ( $Gj\ m^2\ yr$ ) for each activity. The method is conceptually simple, but there are potential difficulties with:

- (a) The resolution of activities. It is assumed that the LUTI model will output floor space data for each zone in the model. However, is this floor space data sufficiently disaggregated by activity to allow a meaningful application of energy use coefficients?
- (b) Specific energy use coefficients. For UK non-domestic buildings, energy coefficients are published (Elsayed *et al.*, 2002) for 32 activity classes, from the NDBS project. It is possible that coefficients considering both activity and built form are also available. For domestic properties, energy use coefficients are thought to underpin the BRE domestic energy models (BRE HOMES, BREDEM). However, these models are thought to classify domestic energy use in c.1000 property types. Clearly energy use coefficients are far more resolved than the activities addressed in the LUTI model; hence aggregate values will need to be identified to match LUTI model activity classes. This aggregation process will require knowledge of the relative frequency of the activities in the urban area (which should be possible given access to NDBS data).
- (c) Sensitivity of energy use to urban form. Note that buildings with the same form house different activities, and that the same activities may be housed in buildings of different form. Thus this method is relatively insensitive to urban form. It will show the difference in energy demand between ‘no development’ and ‘development’, and between developments with different land use mixes. It will be capable of mapping building stock energy use by LUTI model zone. However, for those options with the same level and mix of development, the city total may be similar, regardless of the form of development. This

is likely to be the case for non-domestic development, as specific energy use coefficients relate only to floor area, and not building form. Housing (c. 50% of building energy demand) may be different, as typical coefficients here may relate to built form (flat, terrace, detached etc) and possibly therefore by extension, could be linked to density. It will be necessary to determine how floor space is output in the LUTI model applications for each of the case study cities.

Further information is being sought on studies that appear to have used this approach. This includes the DREAM model (Titheridge *et al.*, 1996), the BRE school of models (BRE HOMES, BREDEM, N-DEEM), and a recent simplified version of the BRE housing model (Johnston *et al.*, 2005). Further advice on urban energy modelling will also be sought from the Carbon Vision Buildings team.

Details are also being sought on the Steadman *et al.*, (1999) Swindon study, which used the TRANUS LUTI model to drive building energy assessment. Details of the energy modelling technique used here do not appear to have been published. However, Johnston and de la Barra (2000) describe a study of Sacramento, in which building energy use (residential only) is calculated using TRANUS as the LUTI model, and the California Urban Futures Model (CUFM) to disaggregate TRANUS zonal outputs of residential land use. CUFM is a non-linear GIS model in which developable land units are identified within a LUTI model zone as a function of developer profitability. Profitable sites are prioritised by GIS overlays of accessibility to roads and services, slope, local government fees, land prices, and several other variables. This approach may also prove valuable with respect to other SOLUTIONS criteria, including the disaggregation of green space, and this provides an alternative approach to the vector to raster conversion technique used with the PROPOLIS project.

### ***10.2 LT method (Neighbourhood Scale)***

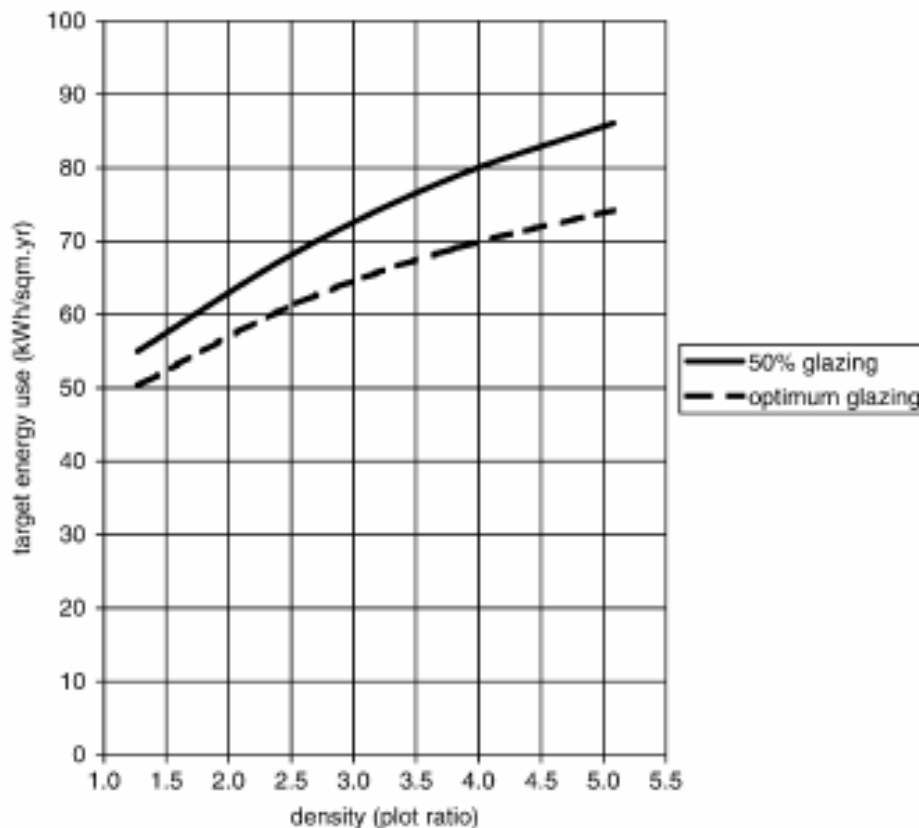
This energy assessment method differs from the activity-energy coefficient method above, in that it gives little consideration to activity, but does give explicit consideration to geometric form. The method has been implemented as a computer based model, and considers density related geometric factors such as building volume, height and plan depth in energy assessment. Designed to support energy efficient design of office buildings, the model has since been used to investigate the impact on energy use (KWh m<sup>2</sup> yr) of the form of groups of buildings (Ratti *et al.*, 2005). In this application, 3-D depictions of the urban form are derived

from a DEM and remote sensed imagery. This would make application of the technique to a whole city problematic for resource reasons (Ratti *et al.*, limited their study to 400 x 400 m areas). However, the theoretical designs of the type being tested at the local level within SOLUTIONS (linear development, pods etc) could be represented directly, without recourse to a DEM or image processing. The practicalities and resource requirements of doing this would need to be established. This method would not give an estimate of energy use as many key factors are not addressed (e.g. use of building, occupant behaviour), but would allow an assessment of the relative impact of built form on energy use.

### 10.3 Simplified LT method

It is possible that the LT method could be used to assess energy use using simplified parameters of building form. Steemers (2003) applied the LT method to a 16 ha area of London, and after assuming numerous standardised values (e.g. U-values, level of glazing, energy using systems), derived a simple relationship relating energy use (KWh m<sup>2</sup> yr) to density (as plot ratio) (Figure 3).

**Figure 3.** Effect of density on energy use for naturally ventilated offices for a London site



Source: Steemers (2003)

For a given density range, the results show that doubling the density typical increases energy consumption by in the order of 25% for the area. The curve relates to naturally ventilated offices only, and was derived to demonstrate the use of the LT method in deriving relationships between urban density and building energy use. It is not known if other such curves are available. If so, it might be possible to also apply these curves at the city scale: energy use is modelled using the activity-energy coefficient approach described above, and the impact of changing form (represented in LUTI model zones as a change in density) is assessed using the plot density – energy use relationship. Further works being pursued in this respect include Baker *et al.*, (1996) and a chapter (presumably by Steemers) in Echenique and Saint (2001).

## **11. Conclusion**

Urban buildings consume at least twice the energy of urban transport, whilst building stock energy use is sufficiently sensitive to urban form to make form a significant determinant on total energy use within a city. This role of form in building stock energy use was theorised in the 1960's and 1970's by writers such as Lionel March and Philip Steadman, and has very recently been demonstrated empirically. It is then appropriate to address built energy use within the SOLUTIONS project. A review of urban and regional energy modelling illustrates that there are no energy models with sensitivity to urban form that could be simply applied within the SOLUTIONS project.

The relatively undeveloped nature of urban energy modelling is exemplified by recent substantial funding from EPSRC to the academic community for model development within the Carbon Visions Buildings Project. Nevertheless, methods suited to SOLUTIONS objectives (plus at least some of the necessary supporting data for the UK) do appear to be available, and offer promise.

It appears that different assessment methods may be appropriate at the two scale at which SOLUTIONS is working (city and neighbourhood). These methods have a different conceptual basis, are sensitive to different metrics of urban form, and differ in the nature of the output (activity-coefficient method would give absolute demand; LT method gives demands which are best used in a comparative manner). There is thus a limited opportunity to directly integrate results from the methods. However, simplified energy-density relationships may be available from LT method applications, which would offer the opportunity to apply a

common method at both scales. Further investigation of the methods described above is underway.

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