ERGOMORPHOLOGY: SOLAR AND ANTHROPOGENIC EXPOSED SURFACE ENERGY BALANCE WITHIN THE BUILT FORM OF THE LONDON URBAN ENVIRONMENT

by

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14 September 2007

The Bartlett School of Graduate Studies

University College London

A Dissertation submitted in part fulfillment of the degree of Master of Science Built Environment: Environmental Design and Engineering

ACKNOWLEDGMENTS

This dissertation is dedicated to my parents, Robert and Judith Hamilton, and Dawn, without whose support this would not have been possible.

I would like to sincerely thank Dr. Michael Davies, my dissertation supervisor, who provided encouragement and assistance throughout the whole process. His enthusiasm and suggestions were always helpful.

In addition, I would like to thank Prof. Philip Steadman and Harry Bruhns who kindly offered their time and insight during the study.

Finally, I would like to thank all the members of the EDE staff, especially Alan Young, who helped create a comprehensive and fulfilling MSc.

Abstract

This study outlines the development of a comparative study of the difference in magnitude of the total incident shortwave solar radiation and the total anthropogenic radiation energy at a built form's given exposed surface area within a representative built form of varying urban environments within the Greater London Authority.

The study provides an assessment and quantification of the anthropogenic energy within the GLA, which is rationalized to the highest spatial and temporal resolution possible. The citywide anthropogenic energy is provided at a $1km^2$ grid. Representative urban environments are assessed and defined based on London's urban characteristics. The anthropogenic energy is then further rationalized to the exposed surface area and compared to of the total incident shortwave solar energy within the representative urban environments. The balance between the two energy sources is compared and the outcome is fit to hourly intensity profiles likely to be seen within the urban environment for different times of the year. The outcome indicates that low-density areas are typically low-rise, predominantly domestic and consume the least amount of energy; that medium and high density areas are of varying height, predominantly mixed, and consume a varying amount of energy; and, that the very high density areas, with high to high-rise heights, are predominantly non-domestic, and consume a large amount of energy.

In addition, the daily exposed surface (wall and roof) energy balance within all representative urban environments is dominated by anthropogenic energy during the winter; that during the mid-season the solar and building energy intensity is dependant on density; that during the summer, solar energy becomes the dominant energy form within the low to high density areas; and, that during an average summer day the roof surface of the very high density area is dominated by the solar energy, but, the anthropogenic energy dominates the canyon surfaces.

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1.0 Introduction

Urban centers are playing an ever more important role in human development; they are soon to become the dominant setting in which people will live and work [GEO, 2003]. All urban environments are the product of man's intervention with the natural environment; they are a complex entity, their physical structure no long reflects the forces of nature, but our very own desires and requirements. The urban climate (the conditions of weather within the urban environment), is subject to a multitude of natural and man-made forces. The recent past has seen a change in the urban structure, one that seeks to overcome natural forces and perform as if unaffected by them; however, current thinking now expresses the need to find balance between these natural and man-made forces. Urban environments are soon to suffer, if they are not already doing so, from issues of energy consumption, unclear energy fuel futures, carbon dioxide and greenhouse gasses emissions and targets, and the need to de-centralise energy use and production; there is a great need to create not only environment-sensitive buildings, but urban centers as well. Keeping this in mind, the effect that urbanism has on its surrounding environment is of great importance to creating these sensitive centers. To reduce the impact that urbanism has on its environment we must understand the impact anthropogenic energy use is likely to have; however, *first* it is necessary to know how much energy within the urban environment is natural (i.e. derived from the sun) and how much is anthropogenic.

This study outlines the development of a comparative study of the difference in magnitude of the total incident shortwave solar radiation and the total anthropogenic radiation energy at a built form's given exposed surface area within a representative built form of varying urban environments within the Greater London Authority.

The aim of the study is to compare the magnitude of difference between the solar and anthropogenic energy of an exposed surface area line[1] using available urban energy statistics and urban morphologic and typologic characteristics. It shows how the proportion of solar and anthropogenic energy of the exposed surface balance is not only a function of seasonal and daily variations, but also the intensity of energy used within a period, which is related to the typology and morphology of an urban environment and where, during certain times of the year, the anthropogenic energy dominates this exposed surface balance, particularly in urban environments with high density and energy consumption and deep canyons that limit solar energy.

The study is in two parts. The first is an assessment and quantification of the anthropogenic energy within the GLA, which is rationalized to the highest spatial and temporal resolution possible. The citywide anthropogenic energy is provided at a 1km^2 grid. The second is a further rationalization of the solar and anthropogenic energy to the exposed surface area within representative urban environments of the GLA. The balance between the two energy sources will be compared and the outcome will be fit to hourly intensity profiles likely to be seen within the urban environment for different times of the year. The first part of the

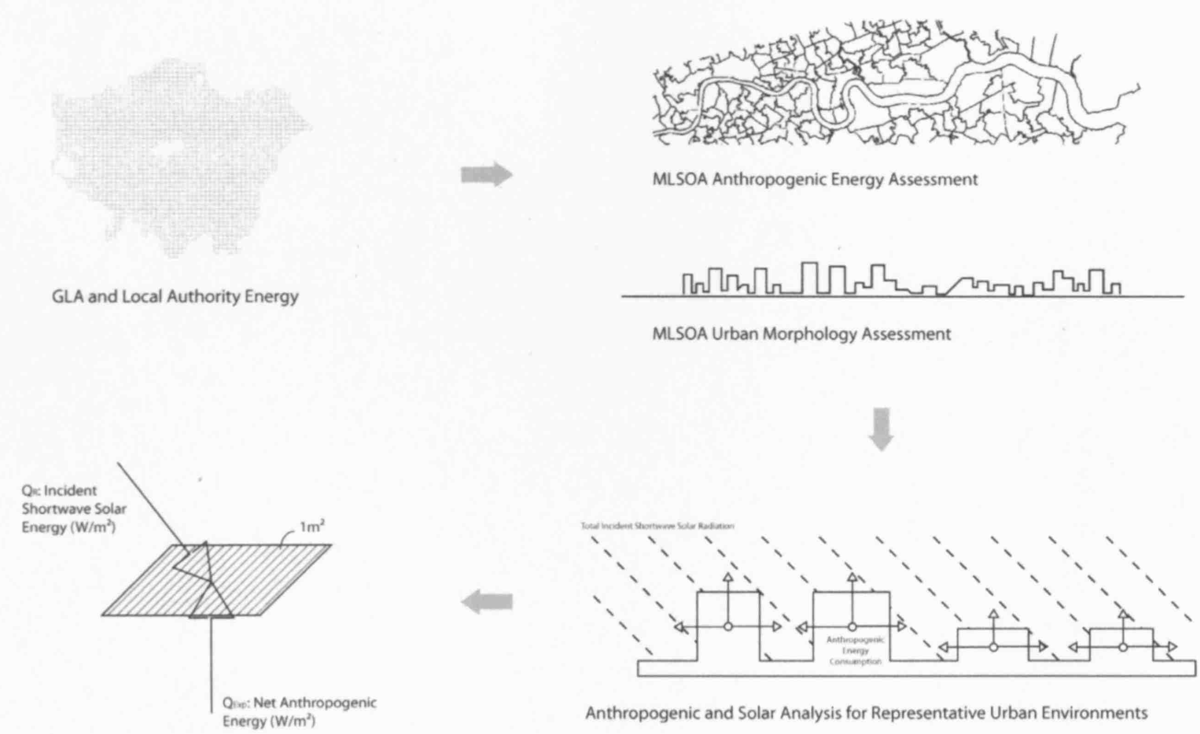
[1] If the urban built form surface is taken as a line which energy arrives at, and one does not consider the lag that fabric would cause, then the amount of shortwave solar energy arriving at that line and the amount of anthropogenic energy arriving at that same line can be compared as an average intensity for a given area (i.e. W/m2).

study provides a 2-dimensional pattern and foundation of anthropogenic energy consumption; the second part creates a 3-dimensional structure of energy and intensity, as it exists in the urban environment.

The study aggregates total energy consumption and exposed surface intensity to a local-climate and local-urban scale (10^2-10^4m), which is a more tangible scale for urban studies, as whole areas and groups of buildings can be assessed. At this scale the individual characteristics of the built form are aggregated and allow for a more 'representative' nature for urban energy consumption and the varying solar energy. The study employs the use of several sets of national and regional energy datasets, simple geographic information databases of urban characteristics, and best available dynamic energy models.

The study allows one to appreciate how the magnitude of anthropogenic energy consumption can play an important role in the urban environment (see Fig. 1), with this energy dominating the exposed surface balance of urban surfaces during particular times of the year. It is also important to the understanding of the 'urban heat island' (UHI) phenomena, which details how urban areas have varying temperatures due to human intervention (i.e. built form, traffic, lack of vegetation and water) compared to surrounding rural environments, by allowing one to understand the magnitude of anthropogenic energy potentially released to the canyon and urban boundary layer.

Urban Ergomorphology Diagram



[Fig 1: URBAN ERGOMORPHOLOGY DIAGRAM]

This study is of interest because it quantifies the proportion of solar and anthropogenic energy within the urban environment at a high spatial and temporal scale. These values can then be used in urban climate modeling and energy projection models for the GLA. Also, quantifying the balance of the solar and anthropogenic energy on exposed surfaces will help identify urban areas with high anthropogenic energy balances, which are likely to add considerable heat energy into the urban environment via fabric heat loss and ventilation heat loss[2]. This would in turn affect the local radiant temperatures, which are likely to have an effect on the sensible temperatures of the urban canyon and the urban boundary layer [Kimura & Takahashi, 1991; Harman & Belcher, 2006].

In addition, the Greater London Authority has indicated that they wish to have a better understanding of the impact that anthropogenic heat has on London's heat island [MOL, 2006, pg. 12], and this would act as a building block towards that understanding. It could also help identify areas that certain renewable technologies would be most appropriate; installing solar devices in areas where incident solar energy dominates the anthropogenic energy, and district schemes in dense urban forms with high energy demands.

[2] The rate and intensity at which the energy escapes is dependant on the characteristics of the building (conduction and heat exchange via walls and openings), which would be difficult to state at an urban scale and will therefore be considered as instantaneous [Sailor, 2004].

2.0 Background Research

An assessment of past research and literature is performed in order to aid in the approach and methodology of the study so as to fully satisfy the issues involved in studying the solar and anthropogenic ergomorphology[3] of urban environments.

2.1 Urban Environments

The urban environment is a heterogeneous and complex entity, it can be classified into varying spatial scales (micro, local, and meso) that consist of fine-scale building elements, walls and roofs, through to buildings and green spaces, urban canyons, city blocks, neighborhoods, zones and whole urban areas; each with its own unique and cumulative effect on the urban climate [Bridgeman & Oliver, 2006, Arnfield, 2003]. An urban area's morphology can be broadly classified into four categories based on density; they are: low, medium, high, and high-rise [Grimmond and Oke, 2002]. The urban built form and its characteristics are an important aspect of the urban environment, as their influence has been shown to have a considerable effect on turbulence, wind, solar radiation, heat storage and temperature, to name a few [Bridgeman & Oliver, 2006]. The effect that urban surfaces have on the roughness sublayer (the layer directly above the urban climate layer) has been shown to be dominated by the ratio of roof area and less so by the geometry of the urban canyon (i.e. sky-view factor) [Harman & Belcher, 2006]. This link helps to identify where the influence of anthropogenic energy may have its greatest effect, within deep urban canyons.

A useful method for quantifying urban climate effects and the relationship between materials and urban morphology is the surface energy balance [Grimmond, 2006a].

$$Q^* + Q_F = Q_H + Q_E + Q_S + Q_A \text{ [units: W/m}^2\text{]}$$

The surface energy balance is a measure of the net all-wave radiation (Q^*) and anthropogenic heat flux (Q_F); Q^* is comprised of turbulent sensible heat flux (Q_H), latent heat flux (Q_E), the net storage heat flux (Q_S), and the net horizontal heat advection (Q_A).

The anthropogenic heat flux of urban areas is the result of heat from vehicles, buildings, and human metabolism, which can be represented in the equation outline by Sailor & Lu, 2004.

$$Q_F = Q_V + Q_B + Q_M \text{ [units: W/m}^2\text{]}$$

With regards to this study, only the anthropogenic heat-flux related to buildings (Q_B) will be considered. Though vehicles and human metabolism are important factors of Q_F they will not be considered for this study, as constraints of procuring reliable data would be difficult and would be beyond the scope of the study to investigate the relationship between vehicle and human heat-flux as it relates to an exposed building surface. Plausibly, a method of inter-surface radiation would be applied to a known quantity of units (i.e. vehicles or persons) in a given space (internal, external) and time.

[3] Ergomorphology is derived from Greek terms for the study of energy intensity (ergon – the process of work) and its form or structure (morphology – the study of forms of things, either its visible shape or configuration). In this context it specifically relates to the process of energy use, and structure within urban environments and what that structure 'looks' like within the built form.

Specifically, this study looks at the varying range and composition of the anthropogenic heat flux of an exposed surface (Q_{Bexp}) through a year by considering the effect of the internal energy consumed by floorspace (Q_{FLR}) and process intensity (Q_{PRC}), and removing any losses (Q_{LOSSES}) that would not occur at the building surface, specifically hot water energy via drains. Anthropogenic heat-flux of exposed surfaces can be expressed as:

$$Q_{Bexp} = Q_{FLR} + Q_{PRC} - Q_{LOSSES} \text{ [units: W/m}^2\text{]}$$

This can then be compared to the total incident short wave solar radiation (Q_R), the major source of incoming flux.

2.2 Solar Energy

Shortwave solar radiation reaches the outer atmosphere with approximately 1367 W/m^2 [World Meteorological Organisation, 2005], this energy intensity is subject to some variation depending on fluctuation from the sun and seasonal distance and solar altitude. The amount of incident shortwave radiation at the surface of the earth is dependent on atmospheric absorption and scattering, cloud cover and particulate reflection. The net shortwave solar radiation at a building surface consists of direct and reflected shortwave solar radiation. Factors that influence local scale incident solar energy are: solar angles, built-form density (sky-view factor, urban canyon ratios), surface aspect, and building fabric characteristics such as albedo, emissivity and glazing. Using the same approach as Robinson and Stone [2004]; where, in order to quantify the total incident solar radiation of a given point [$Q_{\Sigma I}$] on an urban surface under an isotropic sky (equal radiance in all directions), the direct solar energy component ($I_{d\beta}$) (including any parallel surface obstruction) is calculated and the inter-reflected energy ($I_{\rho U.\beta}$ and $I_{\rho L.\beta}$) (including any obstruction above and below the point) and ground reflected energy ($I_{d.gnd}$) (inclusive of the inter-reflection of both canyon walls and any direct radiation) is added. The sum of which provides the total incident shortwave solar radiation for a point, which can be expressed as:

$$Q_{\Sigma I} = I_{d\beta} + I_{\rho U.\beta} + I_{\rho L.\beta} + I_{d.gnd} \text{ [units: W]}$$

The total incident solar radiation on a surface (Q_R) is the sum of $Q_{\Sigma I}$ for every point (the points are based on a grid across an urban surface), which is divided by the total surface area (A). The total incident solar radiation can be expressed as:

$$Q_R = Q_{\Sigma I} / A \text{ [units: W/m}^2\text{]}$$

Using the above solar and anthropogenic energy expressions the energy at a given exposed urban built form surface area line can be quantified and compared for a range of urban environments. The advantage of considering these issues at an urban built form scale is that issues of surface individuality can be avoided and more tangible results can be linked to urban environments.

2.3 Anthropogenic Energy in the Urban Environment

The anthropogenic energy consumed within the built form is made up of fuels used for floorspace energy, which consists of space and water heating, lighting, appliances and equipment, and process intensity (generally used in manufacturing). The consumption of these fuels is dependent on the particular characteristics of the building (i.e. size, location and exposure, building fabric), the services within, and the operation schedule; the magnitude can vary between individual buildings, uses, and times of day. The most common division of energy consumption within the built form is that of 'domestic' (dwellings and spaces for living) and 'non-domestic' (all other built form types). The superficiality of this dichotomy poses a problem for differentiating energy consumption within areas of the urban environment, as issues of aggregation may lead to a misrepresentation of high or low consuming clusters; this is seen in an analysis of anthropogenic energy allocation by land use versus built form characteristics [see Appendix B – GLA Energy Consumption Assessment]. It is discerned that in the GLA, the domestic sector provides a relatively uniform energy consumption pattern between properties, with larger dwellings using consistently more energy than smaller ones in a relatively linear relationship. The BRE suggests that as insulation levels are increased and heat loss decreased, energy consumption in buildings becomes less related to external temperatures [BRE – Domestic Energy Factfile, 2003], though there is certainly still an influence. The non-domestic sector has no uniform relationship; many properties of similar uses will vary in their consumption [Mortimer et al., 2004].

Some studies have solely used building heating as the basis for Q_B [Coutts et al, 2007], however, this may lead to an overly simplified representation of the anthropogenic heat flux as considerable gains within a building are linked to equipment and lighting, which occur throughout the year. In addition, ventilation and cooling devices will expel heat-energy directly to the external environment; for the simplicity of the urban form, this energy can be considered as a part of the surface of the building.

At an individual building scale the energy consumption between two properties can vary considerably. An analysis by Mortimer et al. [2000] of the Non-Domestic Building Stock (NDBS) database[4] indicates the range of consumption for non-domestic buildings even within the same land use category can vary considerably, especially in restaurants and manufacturing premises.

2.5 Anthropogenic Influences in Urban Environments

Despite these issues, studies of American, Australian, Canadian, European, Japanese, and UK cities have shown a correlation between energy consumed and built form density, where more dense areas consume greater amounts of energy [see Coutts et al., 2007; Sailor & Lu, 2004; Yamaguchi et al., 2007; Klysik K, 1996; Harrison et al., 1984].

Several studies have indicated the importance of quantifying the anthropogenic energy and the effect on the urban climate [see Coutts et al., 2007; Ichinose et al., 1999, Taha H, 1997; and Klysik K, 1996]. The Ichinose et al. study of Tokyo quantified the increase in sensible temperatures within the urban environment, as a result of a detailed survey of anthropogenic energy consumed, to be up to 1.5°C within areas of large anthropogenic heat release (between 400 to 1540 W/m^2). The influence was strongest during winter months and weakest during summer, as the shortwave radiation varied along with seasonal daily temperature profiles. The Taha study of several American, Canadian and European cities valued Q_F as a function of the working and resident population and heating and cooling requirements and indicated that anthropogenic heat release was strongest in cold-climate city centers, but was nearly negligible in suburban areas; the study quantified considerably lower Q_F values (19 to 159 W/m^2); the study suggests that an increase of 2-3°C could be seen. The discrepancy in energy consumption per area between the two studies may be attributed

[4] A database constructed from the surveying of 4 English Towns by Brown, Rickaby, Bruhns and Steadman [2000] between 1989 and 1992, fitted to building stock indicators for the UK.

to the Tokyo study having a very detailed mapping of the total anthropogenic energy consumption and built form characteristics versus citywide statistics.

A study by Ratti et al. [2005] considered the morphologic nature of the urban environment and the consumption of energy. They used a surface-to-volume ratio, which describes exposed surface to volume, for three European cities (Berlin, London, and Toulouse) and, along with several other urban parameters, to indicate a link between likely building energy use and the depth of buildings and their morphologic nature (i.e. over-shadowing, passive zones, natural lighting, etc...). The study indicated the importance of including morphology in urban energy assessments.

The range of studies that have looked at quantifying the anthropogenic energy within the urban environment and its effect on the urban climate is considerable, with a variety of outcomes. Despite the variation within the studies, it is noted that having detailed knowledge of an urban site and its energy consumption is very important in creating, if not accurate, then indicative results of the magnitude of built form surface energy. It is also known that the urban environment is affected by the energy consumed within the built form by increasing sensible temperatures, and that quantifying it may help indicate its likely effect.

3.0 London Case Study

The Greater London Authority is used as a case study due to the availability of energy consumption and built form data, the large quantity of energy consumed within its built form, and the extreme variation of the built form morphology. It can also be used as a representative example for other European cities due to the similarities in its general low-rise, densely built, morphology and typology. It is important to note, however, that the outcome of this study is meant to be indicative of exposed surface energy intensity of representative sites within a study area of the GLA, and actual comparison for other cities would be dependent on their own ergomorphic characteristics and climatic influences.

London has a current estimated urban population of approximately 7.5 million people, almost a quarter of the population of England [ONS – Neighbourhood Statistics, 2007]. These people live in approximately 3 million households; a third of these spaces are purpose built flats (1million), with terraced (0.8million), semi-detached (0.5million), converted flat (0.4million), and detached homes (0.18 million) making up the rest; only 56 thousand household spaces, or 1.8%, are located in commercial premises [ONS – Neighbourhood Statistics, 2007]. With regards to energy use, this last point ensures that any errors caused by gross aggregation of domestic and non-domestic energy will not greatly misrepresent mixed-use premises within the GLA, as there are fewer of them.

London's non-domestic sector has significantly changed over the past 40 years, from an industrial manufacturing centre to a high-finance world trade and service sector [MOL – The London Plan, 2004]. As of 2005, over 90% of all employment was located in the services sector and only 5% in the manufacturing sector [NOMIS, 2007]. This employment pattern is mirrored in the energy consumption statistics outlined below, where despite the great variation within industrial applications, the overall industrial consumption within the GLA is low, at approximately 7% of total GLA energy, with 29% of non-domestic energy used in the commercial sector [MOL – The Mayor's Energy Strategy, 2004].

The current domestic energy consumption (as of 2005) for the GLA is approximately 67.2TWh/yr, with the majority of that made up of natural gas and electricity, approximately 79.4% and 20% respectively, with the remaining 0.6% derived from other fuel types. The non-domestic sector consumes approximately 59.9TWh/yr, with 48.8% derived from natural gas, 44.8% from electricity, and the remaining 6.4% from petroleum, coal and other fuels [DTI – Regional Energy Consumption, 2006].

3.1 LECEI Database

The urban land patterns within the GLA provides a partial understanding of the likely energy consumption that occurs over a given time and space. The London Energy and CO_2 Emissions Inventory (LECEI) of 2003 provides energy consumption (in kWh) and carbon dioxide emissions (in tonnes/year) based on the Ordinance Survey's (OS) 1km^2 grid. The database presents values that include energy and fuel, used for domestic, industrial and commercial, and the transport sectors. The built form sectors (domestic, industrial and commercial) accounts for electricity, gas, oils, coal, and renewables and waste fuels; the method of allocation to the built form is based on the office of national statistics (ONS) generalised land use (GLUD) statistics [MOL – LECEI, 2006]. The database helps to indicate a likely distribution of energy consumption across the GLA. However, the use of the GLUD as the method of built form energy consumption allocation in the LECEI database presents several problems, mainly that the GLUD provides an over-simplified version of the Greater London area's built environment. Generalised land use only provides a two-dimensional view of the built form, it does not represent (1) the height of the built form nor (2) any detail of the building use, both important for energy use (see Appendix B: GLA Energy Consumption Assessment). The height of the built form helps allocate energy consumption according the volume, which allows for larger buildings to be better represented. Otherwise, if the footprint area is the same, areas with high-rise apartment complexes may be mistaken as low-rise housing, or high-streets as industrial parks. Large buildings, like apartment complexes, will typically consume more energy for space and water heating, lighting, and equipment and appliances. This aspect is particularly important when analyzing domestic and non-domestic forms, excluding industrial applications that follow no particular built form pattern of use. The GLUD only provides a very simplified division of land use, domestic and non-domestic; though land-use is not a good indicator of energy consumption [Mortimer et al., 2004], it is thought that a further dis-aggregation between non-domestic land types, if only for the composition of building types, would provide a better picture of energy consumption and comparison.

The review of the LECEI database, its limitations and constraints, is a great help to this study and its ability to allocated energy consumption. It also identifies areas that require further research and analysis in order to depict the urban anthropogenic energy structure in a realistic manner. Importantly, having a more detailed knowledge of the GLA's built form would likely improve the accuracy of energy allocation.

4.0 Project Aim & Intent

The project intent is to quantify and compare the energy intensity balance of the total incident shortwave solar radiation and anthropogenic energy intensity on the average exposed surface area line within representative areas of varying urban morphology. This study involves an initial understanding of the anthropogenic energy consumed within the urban environment of the GLA, the morphologic and typologic patterns through the GLA, and the estimated solar radiation falling within the urban environment. Combined, this will provide an indication of the urban ergomorphic structure within the GLA.

The Tokyo study [Ichinose et al., 1999] indicates that the magnitude of anthropogenic energy can have a substantial impact on the urban climate temperatures; the Harman and Belcher [2006] study indicates the relationship between canyon surface temperatures and morphology; this study attempts to add to this body of knowledge by quantifying anthropogenic energy at the local urban scale, rationalizing the anthropogenic and solar energy to the urban form, and comparing the magnitude of anthropogenic energy by applying the energy to known daily intensity profiles.

It is the hypothesis of this study that the difference in magnitude between solar and anthropogenic energy intensity of exposed surfaces is a function of seasonal and daily variation in solar and anthropogenic consumption and urban morphology and typology, where the proportion of solar energy is decreased in deep canyons, which are typically non-domestic, higher consuming urban environments. This likely dominance of the anthropogenic energy on exposed surface areas would increase its importance in urban climatology and provide insight into the sensible effects seen in the micro-scale canyon and meso-scale urban center environments.

This study compares the total incident shortwave solar energy and the net anthropogenic energy consumed, which can be expressed as:

$$Q_{Bexp} \mid Q_R \text{ [units: W/m}^2\text{]}$$

The study is able to quantify the anthropogenic energy consumed within local urban environments, but cannot further disaggregate consumption beyond the 1km or MLSOA scale due to the lack of knowledge of energy consumption by individual properties. This same problem limits any further division of MLSOA's that are much larger than 1km. Therefore, for the purpose and scope of this study, only those MLSOA's that are approximately 1km^2 are assessed in more depth.

5.0 Methodology

The study consists of (1) an initial collection, outline and analysis of the energy consumption characteristics, and influencing factors for the built form of the GLA, from which a pattern of energy consumption at a yearly and (2) daily scale for the Middle Layer Super Output is established; and (3) the related weather patterns will be checked for any possible influences beyond seasonal norms. (4) An analysis of the built form characteristics is undertaken using local geographic information and their energy consumption values; from this a study area is defined within the GLA. The results of the built form characteristics assessment are (5) categorized into a set of four categories, and four representative areas for the GLA are chosen based on their built form characteristics and energy consumption pattern. (6) Models are created for each representative area and are used to estimate the total incident solar radiation within each of the urban types; then the related anthropogenic energy intensity is also established per square meter. The energy consumption is then (7) fit to a daily pattern that reflects the built characteristics of the representative areas; the solar and anthropogenic energy are then compared to assess the difference in magnitude likely to occur.

The following describes each step within the study and the methodology taken, its aim, the data used, the process followed, the assumptions made, the outcome, and validation. The GLA Surface Energy Balance Flowchart provides a visual guide to the steps taken to complete this study (see Methodology Flowchart).

5.1 Energy Statistics

The energy statistics for the GLA and the UK are largely collected and distributed by the Department of Trade and Industry (DTI). The approach to establishing a temporal and spatial energy consumption resolution for the GLA involves an examination of the available DTI data sets, their collection methods, inherent idiosyncrasies, inconsistencies, and limitations.

Gross primary and delivered building fuel consumption data at a regional, and local authority (LA) level for yearly intervals can be obtained for all fuel types (gas, electricity, transport, and 'other') and for total final energy consumption. In addition, a middle layer super output area[5] (MLSOA) data has been developed for the UK in an attempt to provide more localized data for energy consumption patterns; this data is only available for electricity and gas from 2004-06.

Annual gas data quantities are collected from the National Grid from their postcode sector gas sales. The DTI aggregates and re-allocates the data according to the MLSOA level. Where postcode consumption data covers more than a single layer the data is equally divided between the MLSOA's; the same division occurs when confidentiality requires postcode sectors to be combined. The annual quantities data is weather corrected to the National Grid's 35-year trend, and is an estimate of annual consumption under average weather conditions.

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[5] The MLSOA level is part of the geographic hierarchy employed by the Office of National Statistics as a method of providing disaggregated data, in this case energy data. The MLSOA has a relatively consistent population (approximately 5,000 or 2,000 households) and is not subject to frequent border re-arrangement [DTI MLSOA Electricity, 2007].

In order to overcome limitations due to accuracy of the data, only the 2005 gas[6] and electricity[7] datasets are used due to their increased geographic and consumption allocation accuracy[8] (for more information refer to Appendix A: UK Energy Statistics).

Electricity data is collected through the electricity industry from actual meter readings, meter point reference numbers, distribution companies meter point administration system, and collection agents; the data is then merged and mapped according to postcodes and aggregated to the LA level. For the UK, the datum consists of approximately 29 million non half-hourly meters (domestic and small/medium non-domestic) and 85,000 half hourly meters (large non-domestic), where annual consumption is based on annualized advance[9], or an estimated annual consumption (uses historic information and the specific meter profile. Users of less than 50,000kWh/yr are considered as domestic users, with users between 50-100,000kWh/yr as high-density domestic (apartment block, or new estates) or small commercial, above this level are considered non-domestic [DTI Guidance, 2006].

The DTI has also released 2005 middle layer super output area electricity and gas consumption data. The data sets provide estimates of the annual electricity consumption for each MLSOA within each LA in the UK, and distinguishes between four meter types: domestic, Econ7 (domestic), commercial (non-domestic), and industrial half-hourly (large non-domestic users). The annual gas data is distinguished using commercial/industrial and domestic meters, whose division uses the above explained allocation method based on consumption. All domestic sector data is validated via census data and feedback from the LA's. The DTI attempts to allocate all the electricity and gas used by the identified sectors, but the industrial half hourly meter consumption is not allocated to the MLSOA level due to data disclosure issues, and the small number of industrial consumers within the LA. This industrial metering may account for upwards of 80% of the energy consumed within the LA (see Appendix A). This poses a problem for the realistic spatial allocation of a large portion of the non-domestic data to the middle layer level (this issue is resolved using built form characteristic relationships from a data analysis described in Appendix B: GLA Energy Consumption Assessment). All built form energy is allocated to an MLSOA based on statistical relationships of energy of urban characteristics, however, for the purposes of this study, only areas with low, or no, industrial lands are selected for further urban form analysis.

The 'other fuels' (manufactured solid fuels, renewables, industrial petroleum and coal) consumption data is an estimate of the energy used at the LA level, collected via combination point and area source data[10]. The data is not actual and is estimated using models rather than surveys, with estimates largely derived from

[6] The gas data has problems regarding the split between domestic and non-domestic consumption, where users of less than 73,000kWh/yr are considered 'domestic' and those above, 'non-domestic'; this may lead to small businesses being lumped into the wrong category. Also, the data does not identify very high consumers, such as power stations, and ignores very small independent gas transporters (mostly associated with new housing estates) [DTI, 2006]. It is estimated that pre-2004 DTI data covers only 70% of the national gas consumption within the UK; however, later data is greatly improved.

[7] Problems with large industrial users linked directly to the high voltage mains are not covered in the data (represent approx. 2% of UK electricity sales); therefore any central volume allocation users (large non-domestic) within the GLA will not be represented. Also, data quality has changed since 2003, and accuracy in industrial/commercial consumption has improved, where refinements have re-allocated large domestic users who were assumed to be small commercial operations and un-tangible uses (street lighting, un-metered, etc...), thus, using later data sets provides better accuracy.

[8] It is recommended by the DTI, that for comparative purposes, the 2005 data set has the highest level of accuracy

[9] Annualized advance is an estimate between two meter readings

[10] The data is collected by a contractor (OFgem) for the ONS who use a variety of undisclosed methods.

the Environmental Agency pollution inventory of air pollutant (CO2, NOX, SOX) estimates from 1km^2 blocks household survey data, population census data, high spatial industrial and commercial employment data, and industry pollution levels, amongst other minor sources. The data does not account for local renewables consumption. Accuracy for such highly modeled estimates is based on the detailed spatial resolution and the resulting influence on energy consumption and the collaboration of sample collecting. Therefore, the accuracy of the data is limited by its heavy use of modeling, especially for small non-domestic and domestic users, but later data sets (2004 and beyond) are based on finer spatial information, thus increasing accuracy.

The percentage of other fuels used in the GLA built form, when compared to the gas and electricity data, is relatively small, approximately 3.34% of the combined gas and electricity consumed in 2004, and 2.74% of 2003 [DTI, 2005]; most of this energy is from petroleum product use in industrial and commercial applications. Though this does not make the 'other fuels' components insignificant, it simply indicates that the variation of the total consumption due to data set inaccuracies will be marginal.

In order to allocate the 'other' fuels and any un-allocated non-domestic energy according to their MLSOA, an analysis study determined a link between Office of National Statistics (ONS) LA authority level occupied household count and size and domestic energy consumption, and Valuation Office (VO) all-bulk rateable floorspace data and non-domestic energy consumption. The unallocated energy is divvied according to the percentage of household count and all-bulk area within each MLSOA, respective to its sector, which provides the year total un-allocated energy that is used in the final energy summary (see Appendix B: GLA Energy Consumption Assessment).

The summary of the gas, electric, other, and un-allocated energy is tabled in the GLA's MLSOA energy consumption database for 2005 (GMED '05). The database uses the MLSOA identifier as the unique code, which is used as a part of a UK wider super output area hierarchy and will be used as the constant throughout the study. Within the GMED '05, energy consumption within the MLSOA's can be classified into groups of low, medium, high, and very high energy consuming areas.

The GMED '05 provides a table of the total listed fuel energy consumption by MLSOA; the table indicates total energy consumed within the MLSOA and energy consumed per unit area within the MLSOA. The energy consumed within each MLSOA is also further subdivided to a 1km^2 grid. This output can be compared to the rest of the UK, South-east England, and between MLSOA's in order to identify patterns of use.

A comparison between the total MLSOA energy to total incident solar energy within a 1km2 urban form grid for the GLA is possible with some further analysis. A citywide calculation would require that the incident solar radiation at the urban canopy layer area be modified to reflect the energy captured by the canyons. This would require knowledge of the total incident solar energy on the roofs of the built form, the urban canyon solar capture and the amount released back into the environment. The solar capture within the canyon is greatly dependent on its size, orientation and material characteristics [Harman, 2003; Robinson, 2006]. Due to the range in urban form within the GLA the total incident solar energy, as a 2-dimensional value, within the varying urban forms across London is not presented in this dissertation. The calculation process requires built form characteristics that are not presently available to this study, only the incident shortwave solar energy for canyon walls and roofs is presented for the four representative urban environments.

5.2 Daily Energy Consumption

The above available energy consumption data sets provide sufficient information on the yearly consumption patterns of the GLA, but unfortunately no available data exists at a finer temporal scale at the local authority or middle layer super output level. The National Grid provides electricity flow data at half-hourly and 15-minute instantaneous demands for the whole of the UK transmission network, but the data is not valid for local areas[11] and is aggregated due to the restructured local network ownership scheme [National Grid, 2006], thus local and regional demand is not shown.

Instead, the National Grid provides daily gas and electricity data for the whole of the UK disaggregated for England and Wales, Scotland, and Northern Ireland. The National Grid daily gas data is converted from a volume total to an energy total, which is obtained by multiplying the corrected volume by the average calorific value of the gas that is distributed through the grid (approx. 39MJ/m3 as used by National Grid) and dividing it by the kilojoules per hour. The electricity and gas results are summed to provide a total daily energy consumption pattern for England and Wales.

From the England and Wales daily energy totals, the percent consumed by the GLA is established using historic consumption values. From this, each MSLOA's daily estimated consumption of gas and electricity is obtained using its percent consumption of the total annual GLA consumption, as derived from the GMED '05 tables (see Charts and Graphs 1: Historic GLA Energy Consumption). The electricity and gas results are summed to provide the *GLA daily energy totals* consumption table. This outcome provides a sufficient daily allocation value for each of the MLSOA's, in GWh/day, based on the DTI yearly energy consumption patterns and the total daily consumption pattern for the GLA.

This method of using the fraction of energy consumed by individual MSLOA's as compared to the total GLA is the best available tool for estimating the daily temporal scale. Seasonal variations are factored into this method by applying the fraction of consumption to each daily energy total. This method does suppose that every day uses the same fraction of energy. This means that weekends and holidays, where many commercial operations consumption is decreased and domestic energy is increased, are missed. However, because the fractions of consumption are based on net totals for the year, they have already included these increases and decreases and thus will not misrepresent the pattern if looked upon as indicative of the season.

5.3 Climate Influences on Energy

Before the urban anthropogenic energy can be structured into the urban forms, an assessment of the climatic influences on energy consumption is performed in order for the GMED '05 tables to be considered as 'representative' of the normal yearly GLA energy use.

[11] These reports measure system input/output balance, gas trading, shrinkage, weather correction and scaling factor values, price information, and actual demands within the two Local Distribution Zones (LDZ) of the GLA. Though the GLA consumes approximately 60% of the commercial demand within the two LDZ's the use of this data to provide a daily consumption pattern would be misleading, as the LDZ's measurement does not distinguish between the gas used within the zone and the gas being distributed through the zone [National Grid SISR04, 2007].

The regional climate that surrounds London has a considerable effect on the energy consumption patterns of both the domestic and non-domestic sectors [MET Office, 2007]. The National Grid includes a composite weather variable (a measurement of actual temperature, wind-speed, and effective temperature) in their natural gas demand estimates, which is used to include seasonal normals and expected surges in demand [National Grid, 2006].

The MET Office provides National and Regional data for locally measured temperature, sunshine, pressure, wind speeds and rainfall, in the London area. The monitoring stations within London (approximately 10) measure a variety of the above conditions, but the main station data sets come from Heathrow Airport (since 2004) and Greenwich (pre-2004).

Local scale measurements of pressure, rainfall, solar radiation, temperature, and wind direction and speed, in addition to air pollutant data, are available from the London Air Quality Network. There are 150 stations around the GLA, covering a variety of urban locations (urban background, rural, roadside, industrial, curbside, etc...). This local scale data is far more representative of the observed conditions felt within the urban environment of the GLA and acts as a comparative source against the regional Met Office data.

The climate conditions are assessed for normal patterns, as based on historic values, and any anomalies are identified and their possible influence on energy consumption or solar radiation rationalized.

5.4 Land Use – Morphology and Typology

The urban form of London has not changed substantially in the last 45-years; the current rate of demolition and new build construction is currently only ~2-3% [Steadman, 2007]. This slow rate of change is helpful to identify the likely urban built form morphology that is seen within the GLA. In order to link energy consumption to its geographic context beyond that of geo-political boundaries, urban built form and land use features will be helpful in understanding energy consumption

The morphology of an urban environment is the product of the shape of the built form, in both a two and three-dimensional way. The built form plays an important role in energy use within an urban environment. It is defined by the buildings' typology and clustering of activities and their shape, the height, density and orientation of the blocks, for which their particularities (age, exposure, size, and efficiency) create a need for heating/cooling, lighting, and other processes. Individual buildings will vary in shape and height, but at an aggregated urban scale of 1km2 these attributes are more easily unified and urban form patterns emerge.

Though the building stock may not change significantly, the function within the building will likely mirror economic trends, favouring applications that are most valuable given their location. This can be distinguished by the typology of the building; however, this may not accurately provide an indication of the likely use of energy. Instead, typology will be used to create representative urban areas to be linked with the energy consumption databases.

The built form characteristics employed in this study are taken from the Cities Revealed I2I database[12], which uses the National Land use Database (NLUD). Detailed land use and building height provide both a 2-D and 3-D image of the urban form within the GLA. The NLUD contains information on the GLA by

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[12] The Cities Revealed is a geographic image product that links NLUD land classifications to Ordinance Survey lot lines and physical built form polygons for the GLA within a GIS database.

distinguishing between 52 different land use types. This database is compiled using features from the Ordinance Survey and the Department of Communities and Local Government and is assessed using a geographic information system database. The NLUD outlines 13 main groupings and between two and six sub groups; the groups used in the study are: Recreation (indoor), Residential (residential, and institutional and communal accommodation), Community Buildings (institutional, educational, and religious), and Industrial and Commercial (industry, offices, retailing, storage and warehousing, utilities, and agricultural buildings) [NLUD – Classification v. 3.2, 2002].

From this database the land use data is assessed and the total area of the building footprints, in meters-squared, is allocated to each classification within the urban area. The area value for each building footprint is equivalent to the gross external floor area[13]. The height data is derived from stereographic aerial images and is plotted using two key measurements; the first is the height of the building above the sea level (OS national height datum), and the second is the height of the top of the building from sea level, from which the height of the actual building is derived[14] [Cities Revealed, 2007]. A mean built form height is derived for the MLSOA's; this mean height excludes any non-built form entities and is used to provide the volume needed for allocating energy consumption and the exposed surface energy structure.

The outcome of the built form analysis is a set of urban forms that represents not only land use, but also building area, detailed building use classification, average height, open space and volume. These forms are linked with the GMED '05 via the MLSOA identifier code.

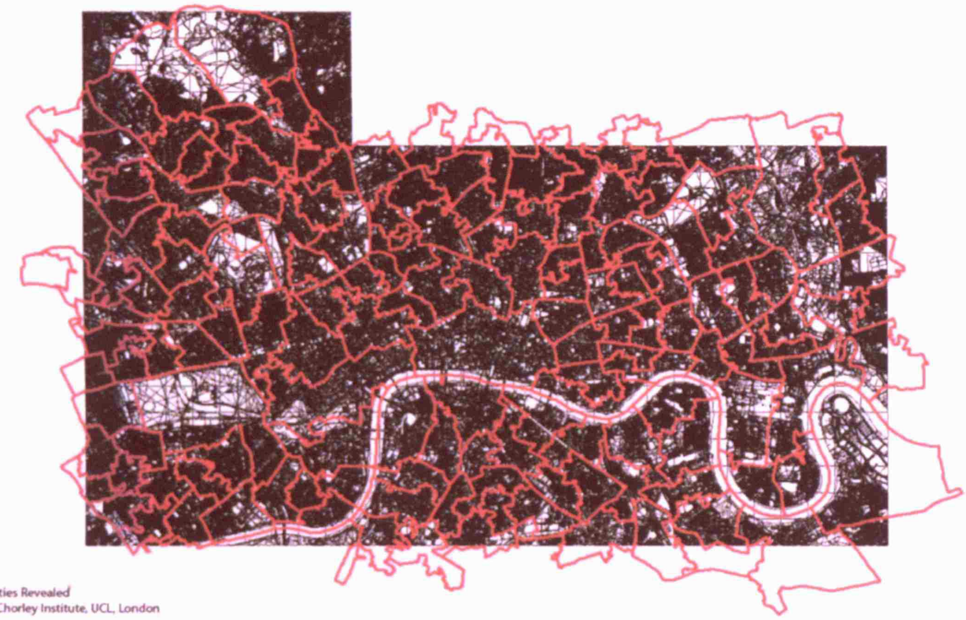
5.5 Representative Site Classification

In order to establish the pattern of surface energy balance in varying urban areas of the GLA, 'representative urban environments' are established using the GMED '05, the *GLA daily energy consumption* values, and an analysis of the urban forms of the MLSOA's.

The 'environments' forms are classed according to their overall footprint and built space, urban canyon width and ratio, and urban volumetric density, which follows the urban land forms established by Grimmond and Oke [2002]: low, medium, high, high-rise. The 'environments' also include a proportion of typology (domestic and non-domestic) and their linked energy consumption, which is classed into low, medium, high and very high energy consuming areas. Due to the sheer size of the GLA, and the vast volume of built form, only the central GLA will be assessed beyond the energy consumption and its initial built form relationship (part 1); the area is 15x10 km through the centre of the city (see Fig. 2).

[13] This measurement method is different than Valuation Office statistics of floor area that measure by net internal area and gross internal area.

[14] Each building polygon will have a minimum of 1 height point, however, any area with a height difference of more than 3m will have another set of height measurement; this helps measure more complex buildings with varying heights.



[Fig. 2: SELECTED MLSOA MAP]

The classifications of all the urban forms are categorized using quintiles; this method allows for an equal distribution of characteristics through each series. The only risk is that certain features may not provide the full range of known values[15]. In addition, the use of quintiles based on the GLA built form trends means that transferability is only valid in urban areas of similar morphology and typology.

Building Footprint

The area of each building footprint is established using the spatial database polygons that have a built form typology and a height greater than 0m. The area (m^2) of these polygons matches with the GLUD, but a detailed typology is listed along with them[16]; the outcome is a building footprint and typology database.

Builtspace Ratio

The *builtspace ratio* describes the amount of area covered by buildings within the MLSOA compared to all other land cover types (see Fig. 3); the ratio is similar to a figure-ground diagram. Low, medium, high, and very high are 0-0.15, 0.16-0.30, 0.31-0.45, and 0.46+ respectively. These divisions are based on an analysis of the generalized land use database, from which typical built space ratios for the GLA are established and arranged in quintiles. The ratio does not describe any 3-dimensional information and is not sufficient alone to describe urban environments.

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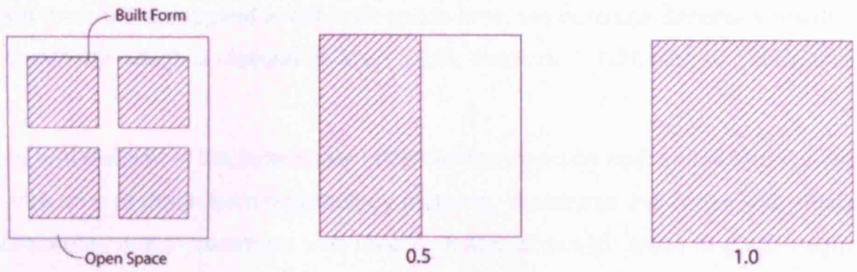
[15] This situation is seen with the mean building height measurement, where a minimum height of 10m is seen in all MLSOA's within the study area.

[16] The database does not distinguish between mixed-use premises, as the classification of the building is based on the land-class, which only associates one sector category per land parcel [NLUD – Classification v. 3.2, 2002], but due to the low number it is not expected this will have a great influence.

Built Space Ratio Methodology



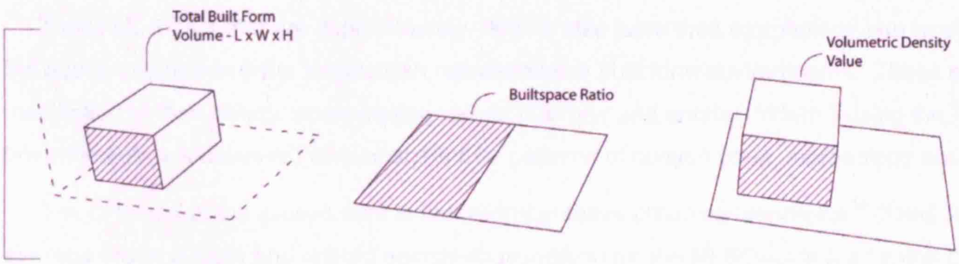
• Indicates the proportion of area covered by buildings within an urban environment

[Fig. 3: BUILTSPACE RATIO]

Volumetric Density Value

The volumetric density value describes the proportion of area that is built space and its 'size' within that 3-dimensional area; it is derived from a multiplication with the builtspace ratio and the mean building height. The value helps to express the area covered in building volume; the value can be used to compare different locations and comments on the gross density experienced within the site, allowing for a comparison between sparse high-rise and dense low-rise areas. However, to understand configuration, the intersecting urban canyons are needed (outline below). Figure 4 graphically illustrates the concept.

Volumetric Density Value Methodology



• The Volumetric Density Value indicates a basic built volume and open space ratio

[Fig. 4: VOLUMETRIC DENSITY VALUE ILLUSTRATED DIAGRAM]

Establishing Representative Environments

First, the areas are divvied by their *built-space ratio*; within these built space bands are varying mean building heights, which range from low (0-8m), medium (9-15m), high (16-21m), and high-rise (22+m). The mean height for each area is then applied to the built space ratio; the outcome describes the MLSOA's *volumetric built form density*, which is classed as low (1-3.0), medium (3.1-6), high (6.1-9.6), and high-rise (9.7+).

The classification and division of the local scale urban environment by *built space* and *volumetric density* is a method that is inclusive of urban form morphology patterns. It ensures that areas with similar built area (m^2) are not misrepresented due to variations with height. It also allows for areas of great height, but low built space area, to be compared with areas of low height and dense built space area.

Building Typology

Solely using morphology for the assessment of built form energy consumption will not completely satisfy the requirements of a 'representative' urban environment. Typology must be considered along with the physical built form assessment. The typology of the urban form is assessed according to its NLUD classification count. Where areas that are considered as 'domestic' consist of over 80% residential, areas are 'mixed-use' when domestic and non-domestic account for 40-60% of the built form, and non-domestic areas consist of over 80% non-domestic building use.

Urban Canyon Width and Ratio

Lastly, the width of the canyon is taken from the measurement of approximately 10 street sections from the GIS database[17]. The street measurements are taken at the mid point of 5 large streets (≥12m) and 5 smaller streets (<12m), where available; these streets are identified as a part of a visual examination of the representative sites. The canyon width can be used along with the canyon height to produce a canyon height to width ratio (canyon ratio). Low ratios indicate wider streets and shorter buildings and higher ratio indicates reduced solar capture within the canyon. When the canyon ratio and volumetric density value are assessed together a complete view of the urban environment emerges; together they comment on the area (its openness), the height of the built form, and the width between the volumes.

Those MLSOA's that are approximately 1km^2 in size have their morphology and typology assessed using the above criterion in order to establish representative built form environments. These environments are then linked to their energy consumption values (GWh/yr and annual kWh/m^2) using the MLSOA code. The environments are assessed and evaluated for patterns of consumption, morphology and typology.

The outcome of the assessment is four representative urban environments[18] (Sites A-D) that depict the average urban density and related energy consumption for the MLSOA's in the central London study area.

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[17] This step is the final assessment of the representative form, as it is derived from the average street width from the study area polygon data. Due to its intensive measurement process it is only performed after the other assessments have taken place, on the 4 most representative sites within each density class (low, medium, high, high-rise).

[18] It is known that these representative sites will have their own characteristics and idiosyncrasies; however, care is taken to normalize any aberrant entities to maximize their representative ability (for more information see Appendix C: Site Characteristics and Idiosyncrasies).

5.6 Urban Environment Dynamic Modeling

3-Dimensional urban models of the representative urban environments are created in order to calculate the total incident solar radiation and anthropogenic energy of an average exposed surface. In order to create a realistic, but indicative, set of surface energy balance values within the representative sites, the dynamic modeling methods are outlined and the modeling program assessed.

The representative site's urban form land maps are assessed and modeled as a $1km^2$ site using a CAD program[19] that provides a simple urban massing model with a re-occurring urban block formation. Groups of buildings and street blocks are modeled rather than individual buildings (which is not practical for an urban form model). The street pattern is re-oriented so that all streets run in an east-west or north-south direction. The size of a typical block is determined by assessing the predominant block size and layout, which uses major intersections of roads, rather than every individual drive paths or alleys, as marking points. The built form within the blocks is developed by tracing out the area covered with building footprints, this ensures rear gardens, central alleys and open spaces are excluded from the built form structure; it does not, however, show gaps and spaces between the buildings. A building volume, using the building block footprints and the mean built form height, is developed for every block. Blocks with rows of detached or semi-detached buildings are modeled as a single long building, although care has been taken to avoid this where possible[20]. The typical block is then reproduced throughout the urban area; the distance between the building blocks is based on the average representative width of the roadways.

Solar Energy Model

The representative urban models are dynamically tested in an energy program for Sustainable Urban Neighbourhoods (SUNtool), a modeling program developed by the European Commission's Fifth framework programme "energy, environment and sustainable development". Its main intent is to optimize masterplans by assessing the proposed development and modeling the microclimate and expected energy requirements based on a description of the development; the model focuses on "resource flow prediction" in the urban environment [SUNTool, 2007]. The model requires that the site size and buildings are outlined and are simulated under a weather file for an identified location in the world, in this case, London. It then outputs the likely energy consumption and resource flows for the buildings within the site.

The model was modified[21] to output total shortwave radiation incident on a building surface (W/m^2) for every hour of a given temporal period. The building surfaces are separated into walls, windows and roofs. The modeling approach used is to model a typical representative block of buildings, with 8 other building blocks surrounding the central block. This ensures that inter-reflected shortwave solar radiation between surfaces is accounted for. The shortwave calculation uses the same method as described above, where the

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[19] The Computer Assisted Drawing program used was Vectorworks. The urban forms were developed and their surface areas extracted to a spreadsheet and linked to energy consumption for further analysis

[20] Some exposed surfaces of the urban form will be reduced, as not all blocks consist of terraced homes, or attached buildings. This aspect of the modeling is not such an issue for medium to very high-density areas, but will cause a problem for low-density or high-rise sites. Therefore, it is likely that the low-density urban form site will be slightly skewed, but will be modeled in this manner for consistency. Also, high-rise sites, with sporadically placed tall buildings, are avoided in the modeling; these sites are not representative of the GLA, though emerging, these forms are still more a North American and south Asian phenomenon. A more appropriate model for very low-density or sprawling urban forms would be of an individual building approach at a finer area scale, say 250m2 block; unfortunately, disaggregating the energy consumption data to this level would be impossible, and would erode the accuracy and validity of the study.

[21] The SUNtool model was kindly modified by Andrew Stone, a member of the SUNtool development team for use in this study.

active building façade is covered with a grid of points from which the total incident radiation is measured, including direct and inter-reflected from opposite surfaces and the ground.

The output of the modeling is a table of values of daily total incident shortwave radiation for each representative urban site. These tables provide the solar energy (Q_R), which can be used for comparison to the anthropogenic energy for the exposed surface balance within the urban environment.

Anthropogenic Energy Model

The anthropogenic surface energy is modeled using exposed surface area values (m^2) extracted from the four representative CAD models. The energy consumed within each representative area is derived from its associated annual energy consumption value (GMED '05) and daily value (*GLA daily energy consumption*). The total annual and daily energy (GWh), which is converted to Wh's, is rationalized to the surface area to provide an energy value per square meter (Wh/m^2). This value[22] accounts for the daily anthropogenic energy incident at the exposed urban building surface and can be compared to the daily solar energy.

5.7 Daily Consumption Patterns

Daily patterns are important for a seasonal assessment of the solar and anthropogenic energy within the urban environment; however, an hourly profiling of the energy as an intensity will provide a far more detailed estimation of the condition experienced. Profiling the energy intensity per unit area for each hour of the day allows for a direct comparison between 'worst' case and 'average'[23] daily solar radiation and estimated anthropogenic consumption patterns.

Standard daily patterns of energy consumption for the UK have not been greatly studied, likely due to the difficulty in establishing energy statistics and their limited transferability between and within their own sector(s), as seen in Mortimer et al. [2002]. A study of Tokyo by Ichinose et al. [1994] detailed the diurnal variability of demand for space cooling in summer, space heating in winter, and annual hot water supply. The profiles developed are indicative of most post-industrial cities in a temperate climate, where the daily occupancy and consumption patterns follow standard business practices. This means that for the domestic sector, consumption peaks for heating and hot water occur in the morning (06:00 to 08:00) and again in the evening (19:00-23:00); space cooling for the domestic sector shows a small spike in the afternoon and evening. A study of typical UK domestic energy modeling has also shown the same twin-peaked energy demand profile, with a peak in the morning (06:00 to 08:00) and again in the evening (17:00 to 21:00) [Yao & Steemers, 2005].

The non-domestic diurnal energy profile is more complicated. Standard building load profile variants have been established by several bodies for use in building energy simulation programs, but they are based on occupancy patterns and are applied to a space within a building for which the simulation will take place. These profiles are used in conjunction with the external environmental parameters; the profiles tend to be

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[22] Issues to be noted with this value are: the variable surface area in the low-density model, the unknown flow direction of the energy, and the lag and attenuation caused by materials and other forces (ignored for the purpose of this study).

[23] The scenarios are a divided between 'worst' and 'average'. The 'worst' case winter scenario is a combination of the highest anthropogenic energy consumption day with the lowest daily temperature and incident solar radiation. The summer worst case scenario has the highest energy consumption, daily temperature and solar radiation levels. The 'average' scenario is the average across a set period season (approx. 120 days for each season – winter, mid, summer – with the mid-season split between spring and fall). The spring season begins on the 60th day, summer begins on the 120th day, fall begins 240th day, winter begins on the 300th day.

either discrete or modular and show the energy consumption as on, off, or base-load. In comparison, several American studies have used degree-days as the basis for fuel consumption in buildings [Sailor D, 2004; Taha H, 1997]; however, this leads to a potential over-simplification of the energy used for other non-heating or temperature related applications. A combination of the Tokyo study and the building simulator profiles shows that the profile of the non-domestic, non-industrial sector peaks for heating early in the day and gradually decreases until 19:00; water consumption is constant but low during work hours; and space cooling is constant, and high during work hours, with a spike after lunch during the hottest time of day.

The diurnal energy consumption pattern for the GLA is derived from the above sources and modified to reflect the total daily energy for both summer and winter in the domestic and non-domestic sector. By performing an arithmetical analysis of the standard consumption patterns and values the profile is normalized for each sector. The outcome provides a total daily consumption demand profile that can be used to fit the total daily energy consumed within the representative site. The daily energy, measured in Wh's, consumed by the representative site is divided by the sector, which divides the percentage of domestic and non-domestic annual energy used within the site. The energy that is not experienced at the building fabric is removed; this consists of hot water losses down the drain, which account for approximately 24% in the domestic sector [Yao & Steemers, 2005]. The assigned hot water losses for the non-domestic sector are more variable at 3-28% annual energy [Mortimer et al., 2000]; for the purpose of this study an average of 10% is used. The energy consumed by sector is then applied to the pattern using the percent used from the daily total within each hour. The outcome is energy intensity per hour, measured in W's; the hourly energy intensity is divided by the total exposed building surface area to produce energy intensity by area (W/m^2). This value (Q_{Bexp}) can then be compared to the total incident short-wave solar radiation.

6.0 Results

The following is an outline of the results for each stage of the study. It includes the product of the quantification of the energy consumption for the GLA in the GMED '05, the GLA daily energy consumption values, the climate analysis, the land-use assessment of morphology and typology, the representative site characterization, the dynamic solar modeling assessment and output, and finally, the daily energy consumption profiles of varying urban environments.

6.1 MLSOA Energy Consumption

The analysis of the DTI's DUKES and the Regional Energy Statistics provide a past and current energy context for the GLA within the UK. The statistics identify a trend of increased total national primary energy consumption of approximately 9% between 1970-2005 [DUKES, 2006]. Despite this moderate increase, the composition of fuels consumed has drastically changed, with the virtual elimination of all fuels aside from natural gas and electricity (mostly derived from natural gas) (see Appendix A: UK Energy Statistics). This is particularly true in the GLA, where gas and electricity account for 72.3% of the total energy consumed for all applications [DTI, 2006].

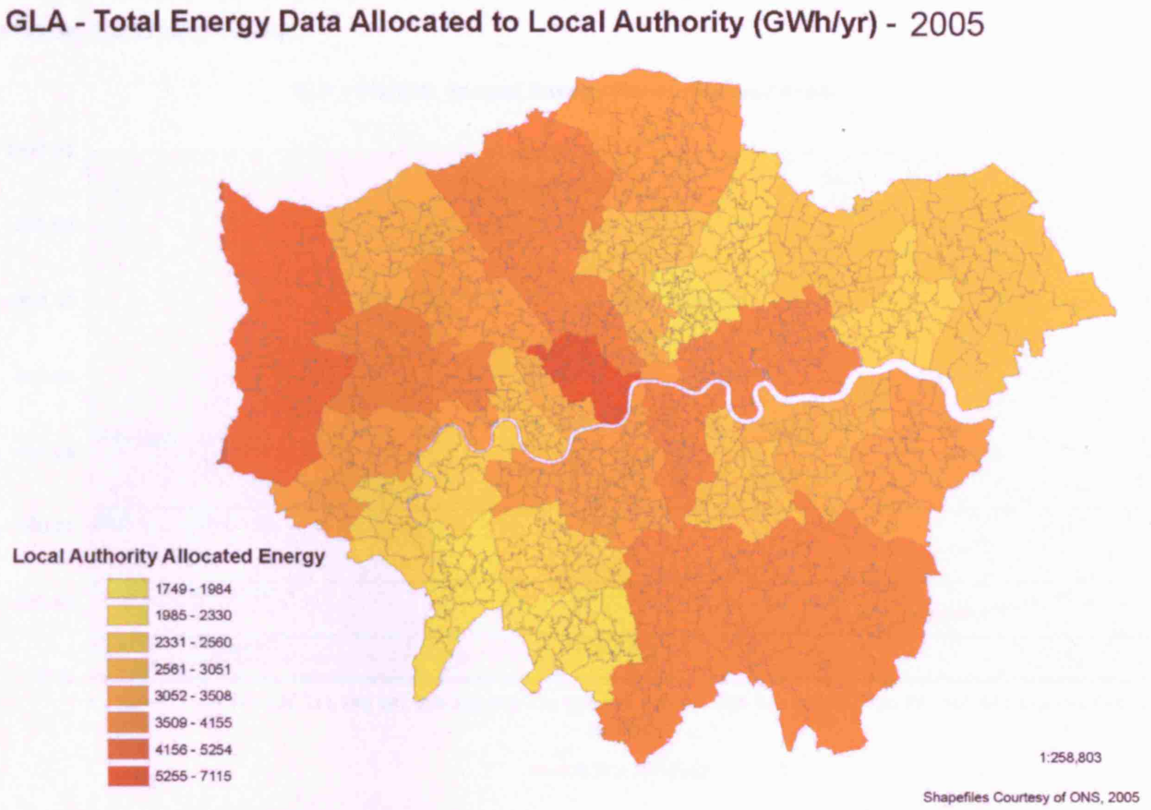
GLA Energy Consumption

The analysis of the DTI Regional Energy Statistics show that the most recent total energy consumption for the GLA in 2004 was 169.7tWh, with 59.91tWh, 67.2tWh, and 42.5tWh's assigned to the non-domestic, domestic, and transport respectively.

GLA Gas consumption by the MLSOA's is approximately 82.7tWh/yr, or 48.73% of the total energy. The average consumption within the domestic sector is 1.6tWh/yr with a standard deviation ±0.53tWh/yr, or 31.5% of the total delivered energy. The average consumption within the non-domestic sector was 29.2tWh/yr, with a standard deviation of ±0.55tWh/yr, or 17.24% of the total delivered energy. Electricity consumption is approximately 40.3tWh/yr, or 23.78% of the total delivered energy. The non-domestic electricity consumption is twice that of the domestic use (26.8tWh/yr and 13.5tW/yr), likely a product of commercial floorspace and process intensity. The 'other' fuels (coal, manufactured fuels, petroleum, renewable and waste) account for a very small percent of the total delivered energy consumption, a combined 2.4%.

The main sources of energy used within the built environment of the GLA are gas and electricity. Gas and electricity account for 96.77% of energy consumption within the GLA, with the 'other' fuels providing the remaining 3.23% (petroleum fuel accounts for 82.34% of the 'other' fuels value).

The DTI's Regional Energy Consumption Statistics provides consumption values for the GLA, the results of which included all delivered fuels used in the built environment at a local authority level. This level is by far the most accurate representation of the GLA energy, as all data is allocated to the local authority level (see Fig. 5).



[Fig. 5: GLA LA ENERGY MAP]

The GLA local authority level energy map provides an initial outline of the location of energy consumed through the boroughs of London. The map indicates very high consumption in two areas, Westminster and Hillingdon. This aggregated view does little to identify the root of energy consumption, as the energy consuming characteristics of the built environment are lost; for this reason, further dis-aggregation to the MLSOA provides a far more realistic portrayal of spatial consumption patterns.

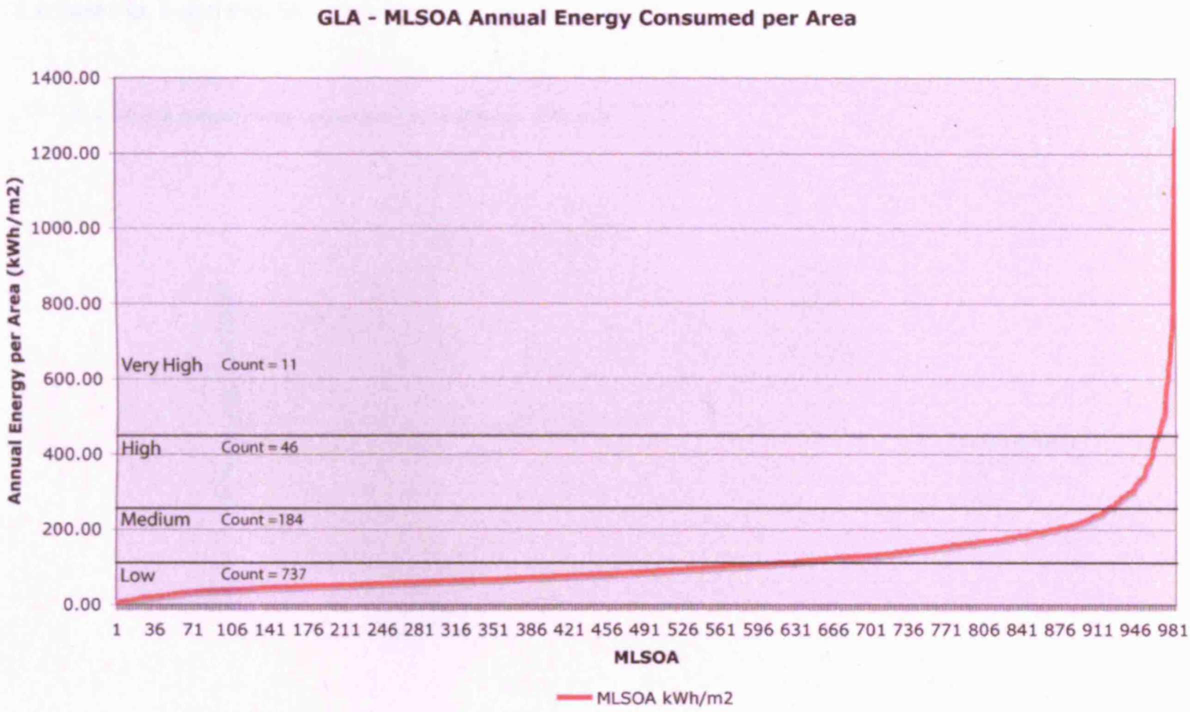
MLSOA Energy Consumption

The total energy consumption for each MSLOA is listed in the GLA MLSOA energy consumption database for 2005, it indicates the make-up of allocated and un-allocated fuels, the domestic and non-domestic allocation values (household count and VO all-bulk floorspace area), and the percent consumption from the total GLA and LA energy.

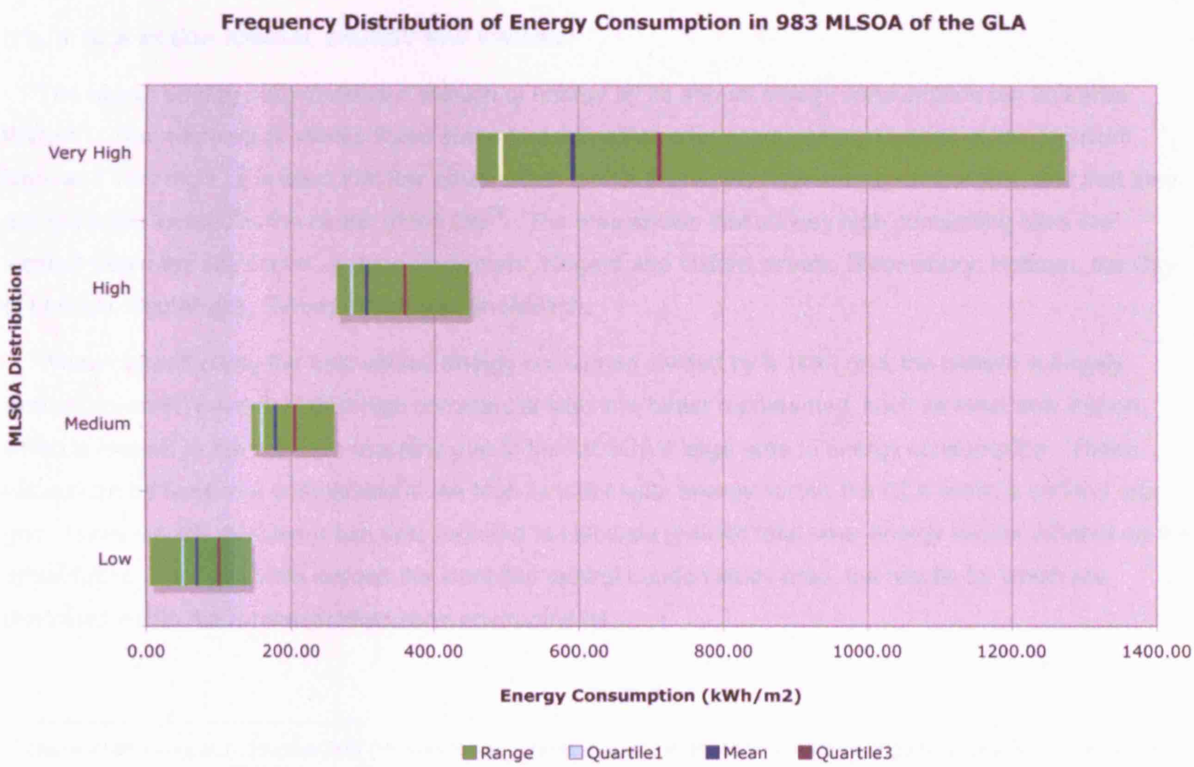
All MLSOA's are grouped according to their consumption level. A table with two classes is created: the total annual energy consumed (GWh/yr), and the total annual energy per MLSOA unit area (kWh/m^2). Both annual values suffer from a heavy skew in the distribution (skew = 4.0748); the division of the energy consumption values is based on an inverse exponential distribution[24] (see Fig. 6), with the lowest consuming <144kWh/m^2; medium 145-260kWh/m^2; high 260-455kWh/m^2; and very-high, ≥456kWh/m^2. Figure 7

[24] The data was sorted by ascending use and plotted; the outcome indicated a heavy skew, causing the median and standard deviation to become null. To avoid a misrepresentation of use, the third quintile is used as a sorting method, by classing the data by its successive third quartiles the data is able to be grouped that considers its exponential form.

indicates the range within the categories, which illustrates that a greater variation in consumption exists in the higher consuming classes.

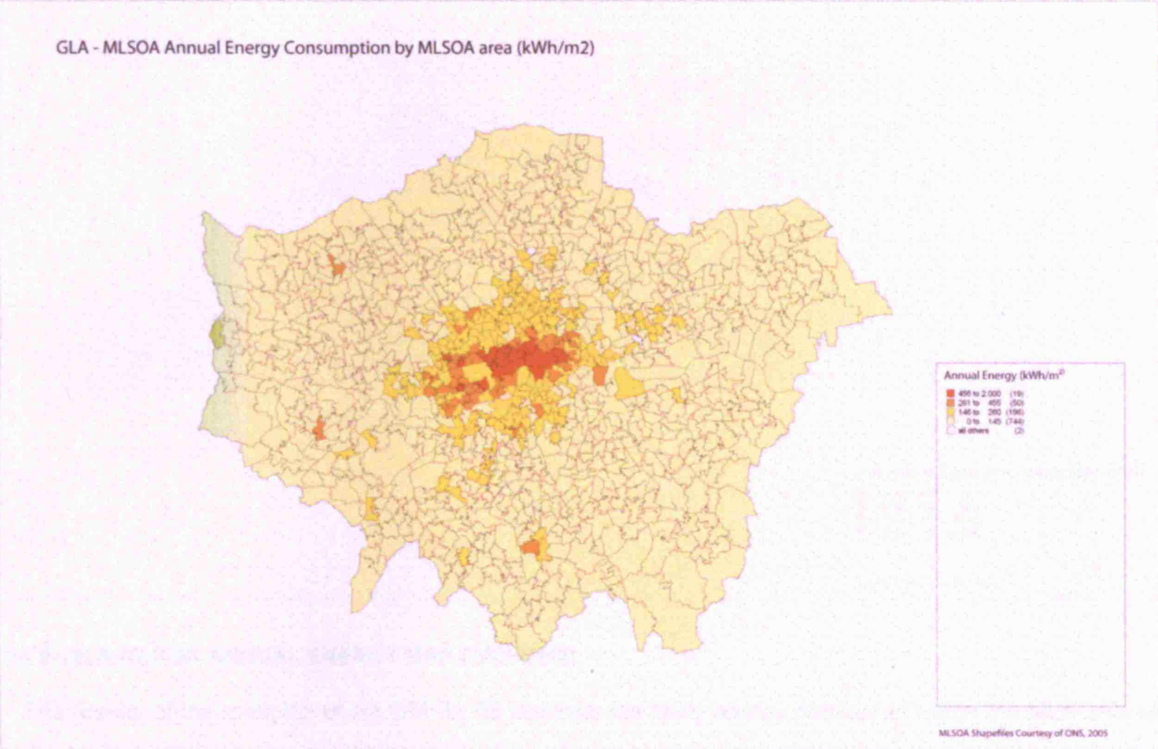


[Fig. 6: MLSOA GWh/kWh ENERGY DIVISIONS GRAPH]



[Fig. 7: MLSOA ENERGY FREQUENCY]

The outcome of table provides spatial mapping of the current energy consumed within the MLSOA's for the GLA (see Fig. 8 and Fig. 9).

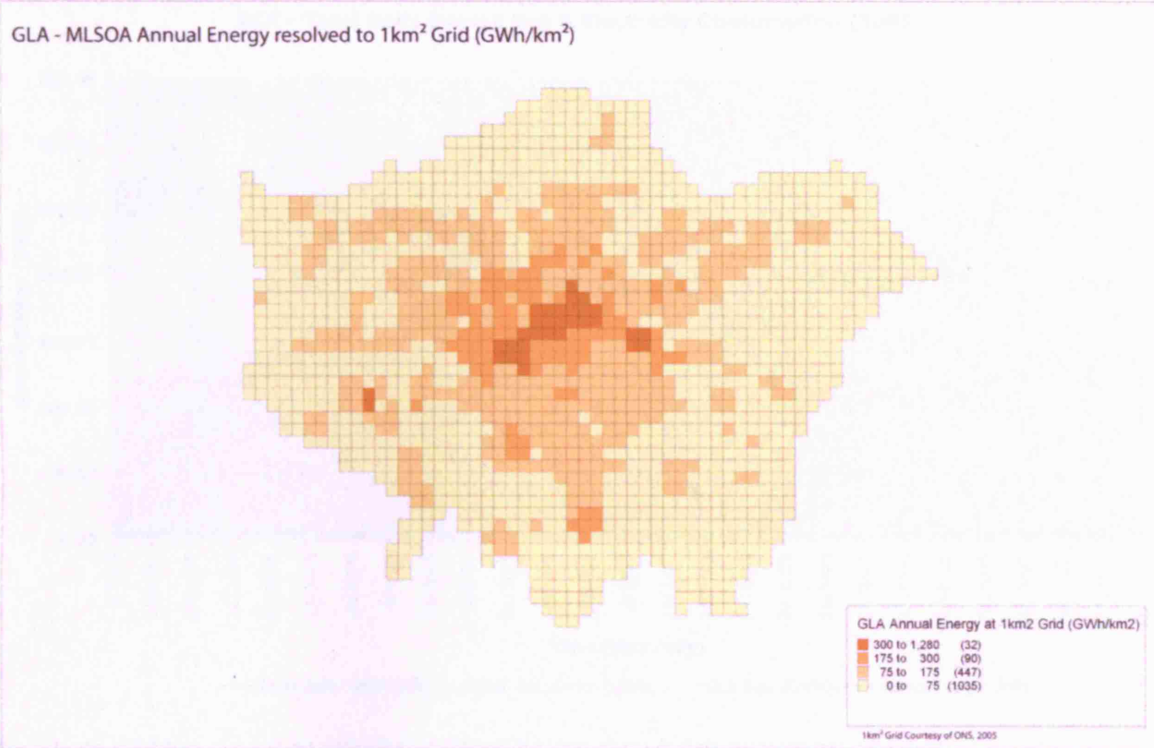


[Fig. 8: GLA MLSOA ANNUAL ENERGY MAP KWH/M2]

The above energy map displays a division of energy by its annual energy consumption per unit area kWh/m^2. The mapping illustrates those areas that are within energy consuming classes of low, medium, high, and very high. It is seen that few areas within the GLA are very high energy consumers, and that they are generally located in the center of the city[25]. The map shows that all very high consuming sites are located within the city center, around Parliament, Regent and Oxford streets, Bloomsbury, Holborn, the City of London, Southbank, Canary Wharf and Shoreditch.

When classed using the total annual energy consumed divided by a 1km^2 grid, the pattern is largely similar; however, several known high commercial sites are better represented, such as Heathrow Airport, which is missed in the previous mapping due to the MLSOA's large area to energy consumption. These values can be used in a comparison to the total incident solar energy across the GLA within a defined urban grid. However, the detailed urban data required to calculate realistic total solar energy values incident on the urban fabric is not available beyond the identified central London study area, the results for which are illustrated within the representative urban environments.

[25] There is an exception, Harrow 020 (Wealdstone), where due to the allocation methodology this area is classed as a high consuming area. This area contains a large industrial park and because the allocation of mainly non-domestic energy favours those areas with higher non-domestic floor area compared to the rest of the local authority, it is allocated a large amount of energy.



[Fig. 9: GLA MLSOA ANNUAL ENERGY MAP GWH/KM2]

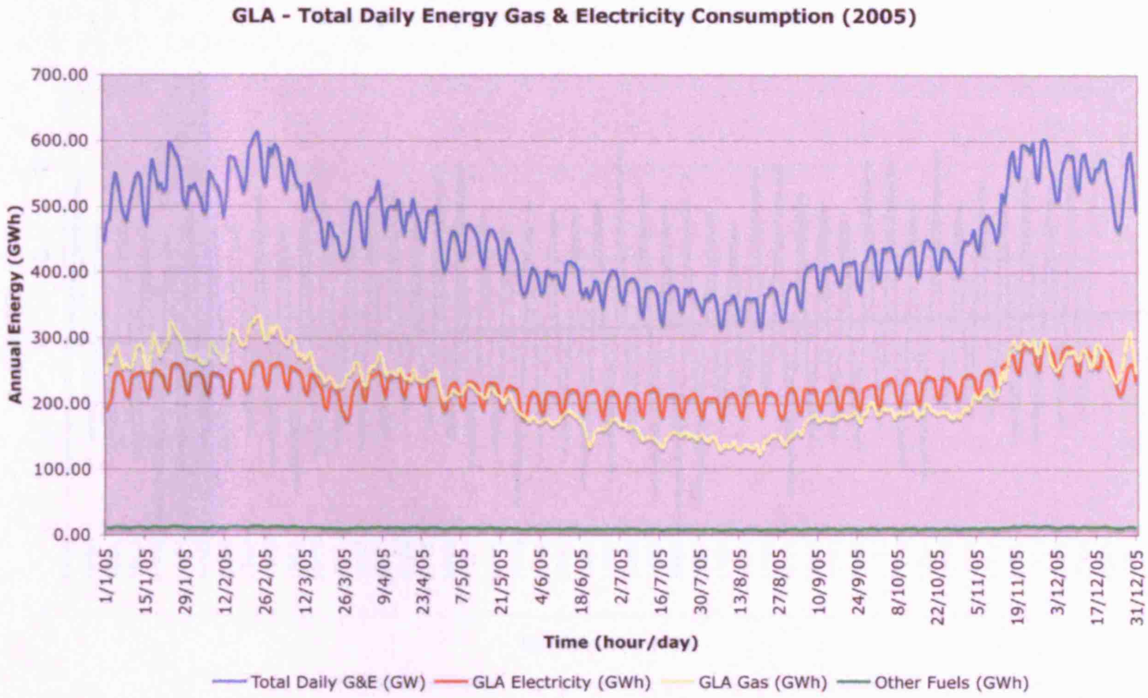
The results of the mapping of the GMED '05 illustrate the likely energy consumed within the MLSOA's of the GLA. The map provides insight into the amount of energy, but does not fully explain why these areas consume more than others. Alone, these values are not sufficient for use in the modeling of the anthropogenic energy at the exposed surface area because they only provide a 2-dimensional value of energy. The values are used to further rationalize beyond this spatial and temporal scale.

6.2 GLA Daily Energy Consumption

Using the 2005 National Grid daily gas demand data and half-hourly electricity demand data for England and Wales the daily energy consumed within the GLA and the MLSOA's is determined.

The annual percent of energy used by the GLA from England and Wales[26] (12.5% electricity, 7.5% gas) is applied to the daily statistics and an added 2.3% of the daily total of gas and electricity to represent the 'other' fuels, which in turn provide a total daily energy (GWh) consumed. The sum of the daily energy consumed in the GLA and the total annual energy match very well. The outcome (see Fig. 10) indicates the seasonal variation of energy consumed within the GLA, with gas data following a temperature-driven form and electricity data showing a slight variation with seasonal temperature and sun hours, and a steady consumption through the summer.

[26] An analysis of the past 4 years of regional energy consumption data indicates that the GLA uses approximately 7-8% of the total daily gas consumption for England and Wales, and approximately 12-13% of the total daily electricity consumption for England and Wales.



[Fig. 10: GLA TOTAL DAILY GAS ELECTRICITY & OTHER FUELS CONSUMPTION GRAPH]

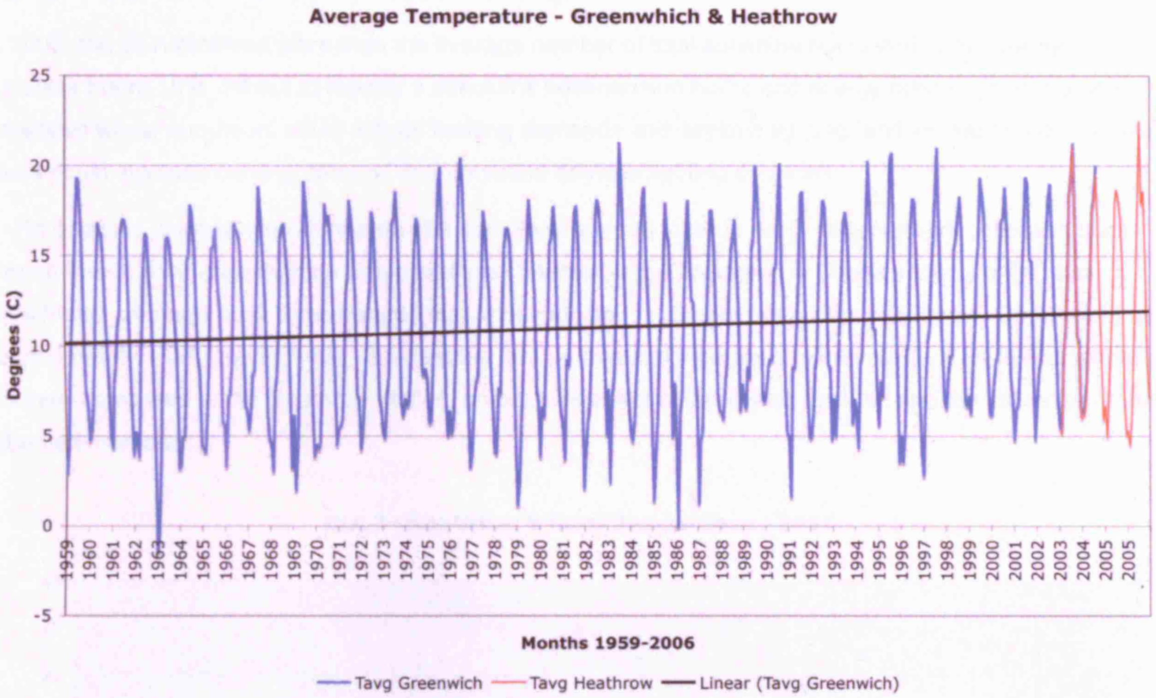
The daily energy consumed within each MLSOA, using the percent consumed from the total, follows the same trend as the annual consumption, with the magnitude modified to reflect the daily total.

With an understanding of the limitations given to the use of an identical daily consumption standard, the total daily energy consumed within the MLSOA is helpful in providing a comparative energy value (GWh). However, simply comparing this daily energy value to daily solar energy will not provide a complete temporal or spatial assessment of the urban environment, as this value of anthropogenic energy is 2-dimensional and must therefore be further rationalized to the urban form and an hourly scale in order to illustrate the ergomorphic nature of the GLA.

6.3 Energy Weather Influences

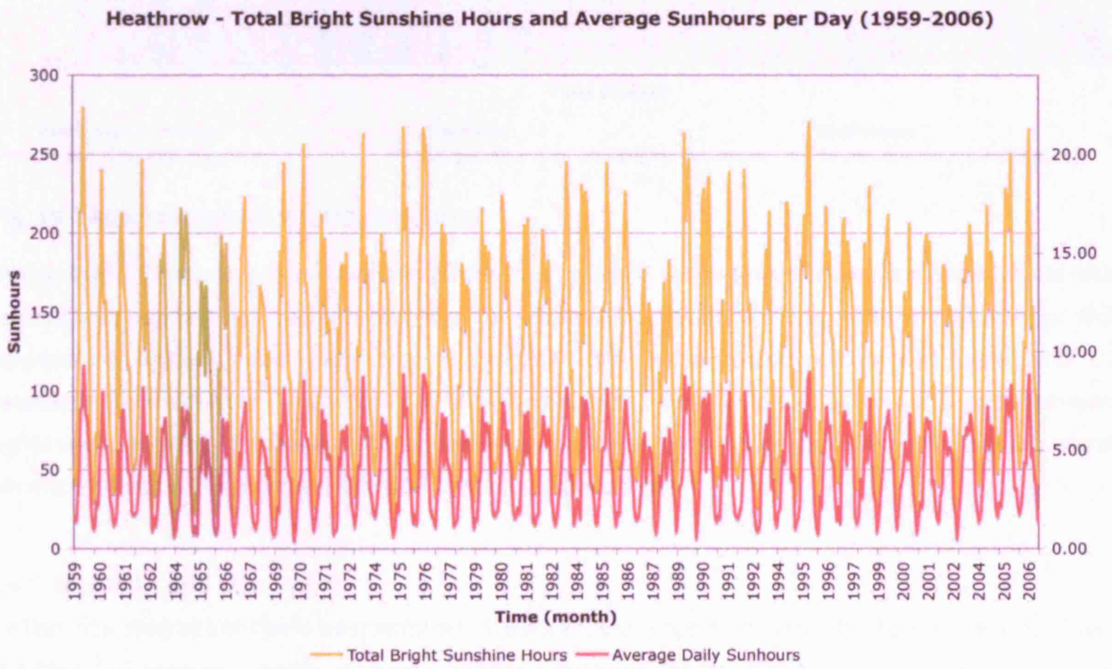
The energy consumed within a year will follow seasonal trends, which are related to the temperature and wind speed (space heating and cooling), sun hours (lighting), as well as constant base load requirements (hot water, electricity for appliances and equipment, and process). The representative nature of the 2005 energy-year is assessed for any possible anomalies due to climatic conditions.

The Graph below (see Fig. 11), which shows historic temperature (1952-2005) data for the GLA, indicates a slight rise in the mean temperature. For the sampled year of 2005, the observed mean monthly temperatures are well within the historic average. The observed annual average for 2005 was 11.8°C, and the five and ten-year average is 11.86°C and 12.11°C respectively. The monthly max and min for 2005 is 15.7°C and 7.9°C, which are within the ten-year average of 15.8°C and 8.3°C. A peak temperature of 23.2°C was observed in August, compared to a peak temperature of 26.9°C in 2003.



[Fig. 11: METOFFICE HISTORIC TEMP AVERAGE]

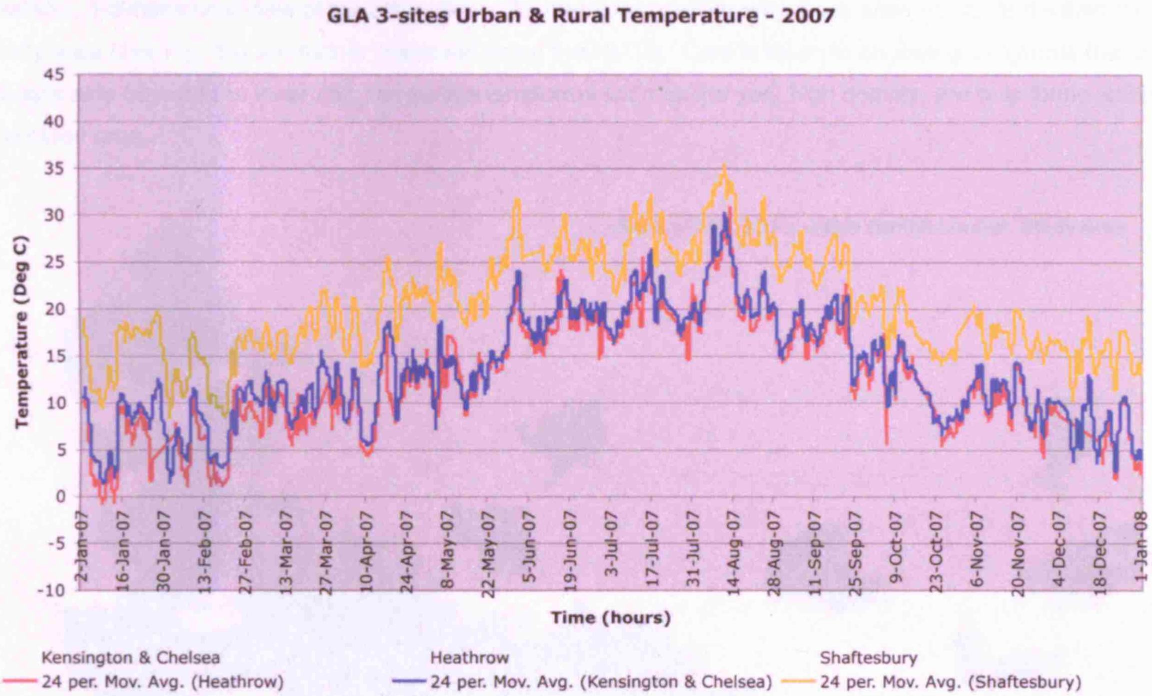
The average number of yearly bright sun hours from 1959-2006 is 1496.3hrs; the total for 2005 is 1684.5hrs (see Fig. 12). This average increase in sun hours was during the summer, where August peaked at 250.4hrs. The average historic number of sun hours per day is 3.97hrs/day, with a peak of 9.32hrs/day in August 1959; the number of sun hours per day for 2005 was 4.6hrs/day, with the highest average during August with 8.1hrs/day.



[Fig. 12: AVERAGE SUNHOURS GRAPH]

In 2005, the GLA received more than the average number of total sunshine hours and daily average sunshine hours. It is difficult to identify a direct link between sun hours and energy consumption; however, increased winter sun hours could reduce heating demands and daytime lighting, and increased summer sun hours could increase cooling demand and decrease daytime lighting demands.

An analysis using temperature data of a sample of several London Air Quality Network collection sites around the GLA indicate that the urban stations (Shaftesbury, Kensington & Chelsea town center) tend to have higher average peak temperatures than those located in rural or open sites (Heathrow, Greenwich) by approximately 1-5K (see Fig. 13). Shaftesbury has an average increased temperature of 5K for the whole of the year compared to the Heathrow station, an obvious effect of the station location and the influence of the urban environment.



[Fig. 13: LAQN TEMPERATURE COMPARISON]

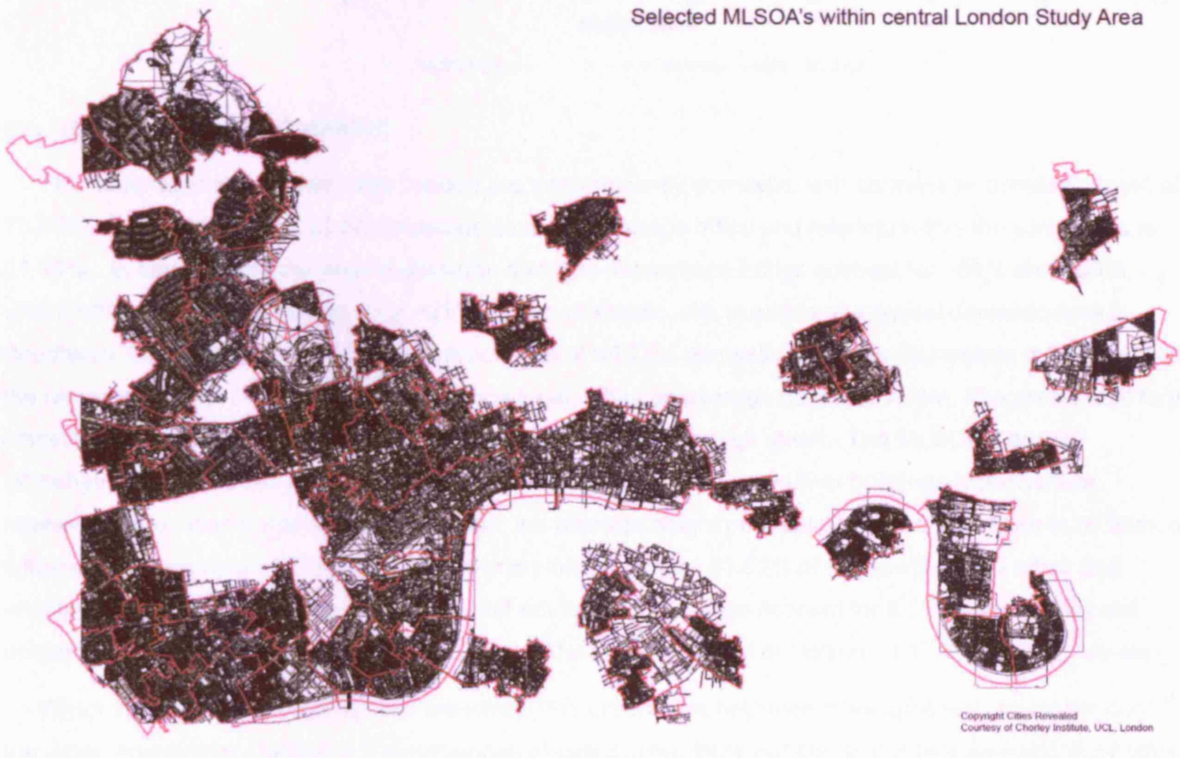
The analysis of historic climate trends indicates that the 2005 yearly temperatures are very close to historic patterns and can be taken as representative. In addition, the influence of the urban environment on local temperatures is also obviously apparent, as the LAQN Site analysis would indicate (see Appendix D: Climate Assessment). Identifying the dominant heat components that contribute to those urban areas experiencing higher average yearly temperatures is an important part of understanding the urban environment, and the influence it has on the urban climate and its related phenomena.

6.4 MLSOA Land Use

The total area of London is approximately 1,596km^2; the urban form consists of approximately 138km^2 and 75km^2 of domestic and non-domestic building area respectively. The area of road within the GLA is

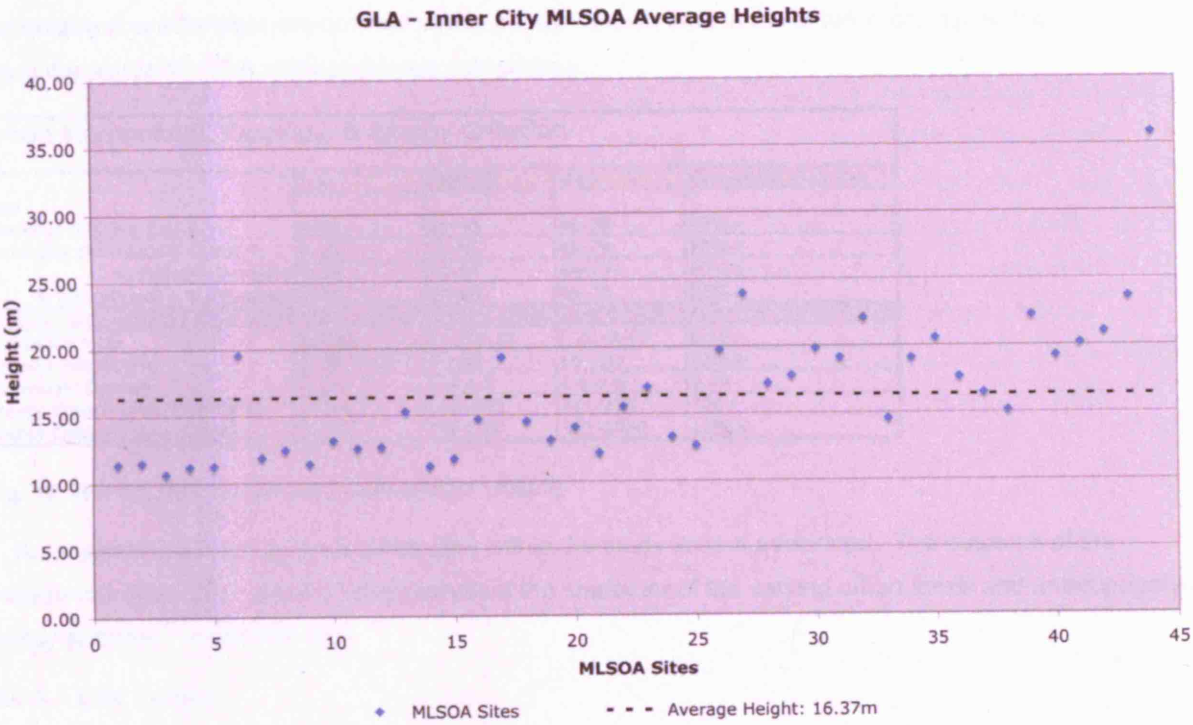
195km^2; the area of domestic gardens and green space is 990km^2, or ~62% of the total area [ONS – Neighbourhood Statistics, 2007]. The difference in area between the built space and non-built space can be seen in the *builtspace ratio* of 0.13, which defines a low-density urban form. This superficial analysis of the built area does little to provide any information on the actual morphology or typology of the GLA, and allocating energy by built area alone is not sufficient. An example is to compare Hackney 027(Shoreditch) and Tower Hamlets 029 (Canary Wharf), each have an area of ~1.0km^2. The area of domestic (0.082km^2 and 0.068km^2) and non-domestic (0.282km^2 and 0.294km^2) built space area is similar, the difference in energy consumption indicates that Canary Wharf consumes 434.56GWh/yr and Shoreditch consumes 262.93GWh/yr, or, 39.5% less than Canary Wharf. If built area were used as the allocating factor, then these two areas would have been assumed to use similar energy. This helps validate the importance of using morphology in the allocation of energy.

An assessment of the GLA's morphology, using the NLUD's building sector categories provides a more realistic, 3-dimensional view of the urban form. As mentioned earlier only those sites ~1km^2 and within the study area (see Fig. 14) are further assessed using the NLUD. Care is taken to choose urban forms that are transferable beyond the inner city, but certain landforms such as the very high density, are only found within the study area.



[Fig. 14: MAP OF GLA ASSESSED AREA]

The assessment yielded results on the height, type, and urban density for the inner city area. The average height for the study area is approximately 16.3m, or 5-6 stories; the maximum average is 35.8m in the City of London, and the minimum average is 10.7m in Southwark 003. The outcome of the height analysis identifies those areas with significant height variations where the average height is affected by large outliers, as seen in the City of London[27] and Tower Hamlets 029 (Canary Wharf), but that the majority of sites are within ±4m of the average (see Fig. 15).



[Fig. 15: AVERAGE HEIGHT GRAPH]

The majority of sites within Inner London are predominantly domestic, with an average domestic count of 70.45% of all buildings and 29.55% non-domestic; the average office and retailing within the same area is 21.44%. In comparison, the area of domestic and non-domestic buildings account for ~54% and ~56%, where office and retailing account for ~25% on non-domestic. An example of a typical domestic area is Southwark 001 (North Rotherhithe), which consists of 96.77% domestic buildings count (area = 81.13%) with the remainder a mix of office, retail, and educational; it has an average height of 11.4m. The area's built form statistics illustrate a predominantly low-rise domestic area with a high street. The MLSOA's around Whitehall, Regent Street, Holborn, and the City of London consist of ~84% of buildings (count) office, retailing or educational and only 6% domestic; the average height of these central London sites is 24.95m, or 8 stories. An example of a higher density site is Holborn, where 81.57% of the buildings are office and retailing (area 68.28%), where institutional and educational buildings account for 8.5% (area 12.5%) and domestic account for another 8.2% (area 2.7%). The average height of Holborn is 19.25m, or 6 ½ stories.

When the height and building uses are joined, the urban form becomes more apparent; no longer does the urban environment exist in a 2-dimensional, bi-categorized form, but one that is inclusive and illustrative of the morphologic and typologic setting. Though sector type is not directly used for energy allocation, it helps to set the context of the representative urban environments. The database of the study area is compiled with the above listed urban form factors by their unique zone code and are linked to the GMED '05 and *daily energy consumption* table, (see MLSOA Urban Environments Table).

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[27] The heights of the buildings within the City of London vary considerably, ranging from a maximum of 180m, an average of 35.8m, and a standard deviation of ±21m.

6.5 Representative Site Selection & Idiosyncrasies

From the GMED '05 table and urban form table, four representative sites are chosen (any idiosyncrasies and unique characteristics are outlined at this point). Shown here is the criterion chart (see Fig. 16) within which the above MLSOA study areas are categorized.

Urban Morphology, Typology, & Energy Criterion				
	Low	Medium	High	Very-High/ High Rise
Area	-	-	-	-
Domestic Building Count %	0-20	21-45	46-79	80%+
Non-domestic Building Count %	0-20	21-45	46-79	80%+
% Office + Retailing	0-20	21-45	46-79	80%+
% Educational + Institutional	0-20	21-45	46-79	80%+
Builtspace ratio	0-0.16	0.17-0.30	0.31-0.45	0.46+
Average Height (m)	0 - 8	9 - 15	16 - 21	22m+
Volumetric Density	0-1.3	1.4-4.5	4.6-9.6	9.7+
Energy Consumption (kWh/m2)	0-144	145-260	261-455	456+
Energy Consumption (GWh/yr)	0 -100	101-300	301-1000	1001+

[Fig. 16: REPRESENTATIVE SITE CRITERION TABLE]

An analysis of all the representative sites within the study area is performed. The outcome of the analysis identifies four sites that best represent the character of the varying urban forms and anthropogenic energy patterns[28] within the GLA.

Site A – Low Density

The chosen site that best represents a low density urban form within the chosen study area is Tower Hamlets 030, the south-west tip of the Isle of Dogs. The area is predominantly domestic (96% count), with a mix of education buildings (1.1%) and retail (1.6%) and other (0.3%). The *builtspace ratio* is 0.14, indicating a low density; there are no parks or large open spaces that affect the results. The average height is 11.23m[29]. The average canyon width is measured at 25m, with a canyon ratio of 2.2. The volumetric density is 1.5; this, along with the canyon ratio indicates relatively small volumes separated by domestic gardens, and roads. The energy consumed by the MLSOA is 78.17GWh; this low energy use is characteristic of all the low density sites within the study area, as is the high-domestic building count.

Aside from the issue of the average height of the buildings, this site is a good representative example of a low density and energy consuming urban form.

Site B – Medium Density

The chosen site that best represents a medium density urban form within the study area is Westminster 002 (Abby Road area north of Lords Cricket Ground). The site is predominantly domestic (92% count), with some educational (1.6% count) and retail (4.8% count). The builtspace ratio is 0.19; domestic gardens and roads make up the majority of open space. The average height is 13.14m; the area is marked with a mix of mid-rise apartments and terrace homes. The average canyon width for this site is 23m, with a canyon ratio of 1.7. The volumetric density value

[28] Only the annual energy consumed within the MLSOA is used in this assessment. It will be modified according to exposed surface area, rather than MLSOA area.

[29] There are no MLSOA's in the study area that have an average height below 10m. Instead a 'closest-to' approach is taken and any errors in the results will be considered.

is 2.5, indicating medium volumes surrounded by generally wide streets. The energy consumption within this medium density area is approximately 144GWh/yr. The energy values within the study areas with density values within the medium range all consume between 100-300GWh/yr.

Site C – High Density

The chosen site that best represents a high density urban form within the study area is Camden 026, Fitzrovia and UCL hospital. The site is predominantly office and retailing (60% count), educational (12.4% count), some domestic (19.6% count) and a general mix of other building uses. The *builtspace ratio* is 0.45; the site has one small green square (Fitzroy Square), with roads and alleys making up the remainder. The average height is 16.48m[30]. The typical canyon width is 15m, with a canyon ratio of 0.9. The volumetric density value is 7.36; indicating larger volumes surrounding by smaller open spaces, where the height and width of the buildings and canyons is close to equal[31]. The energy consumed within this high density area is 385GWh/yr. All high density areas had consumption values between 350 – 750Gwh/yr.

Site D – Very-High Density

An example of the very-high density found in the study area is Westminster 013, Oxford and Regent Street. The site is predominantly office (66.2% count), retail (17% count), a very small number of domestic (5%), and a mix of institutional, recreational and educational. The *builtspace ratio* is 0.59; any open spaces are either roads and alleys or small pedestrian areas. The average height is 22m. The average canyon width of this area is approximately 12m; the canyon ratio is 0.55. The volumetric density is 12.3, which indicates large buildings with little open space and narrow streets; the built form plays a dominant role in the urban environment. The energy consumed within this area is 1635.92GWh/yr.

6.6 Urban Environment Modeling

The urban morphologic characteristics of the four representative sites are modeled in a CAD program for use in the SUNtool program; the outcome provides 4 representative models of the varying urban forms within the study area.

Site A – Low Density

The model of Site A creates long blocks of attached terrace homes approximately 90m wide by 475m long and 14m deep. The void within the building block simulates the large domestic garden plots and rear lanes. The width between the building blocks is 25m. The heights of the buildings have all been extruded to 11.2m.

Site B – Medium Density

The model of Site B has slightly smaller blocks, which are 60m wide by 230m long and 16m deep. The void within the buildings simulates domestic gardens and rear lanes. The width between the building blocks is 23m. The heights of the buildings have all been extruded to 13.2m.

[30] The BT tower is removed from the table and does not skew the representative height.
[31] This indicates the streets are now taller than the road width, thus increasing overshadowing on opposite buildings even during higher altitude solar positions.

Site C – High Density

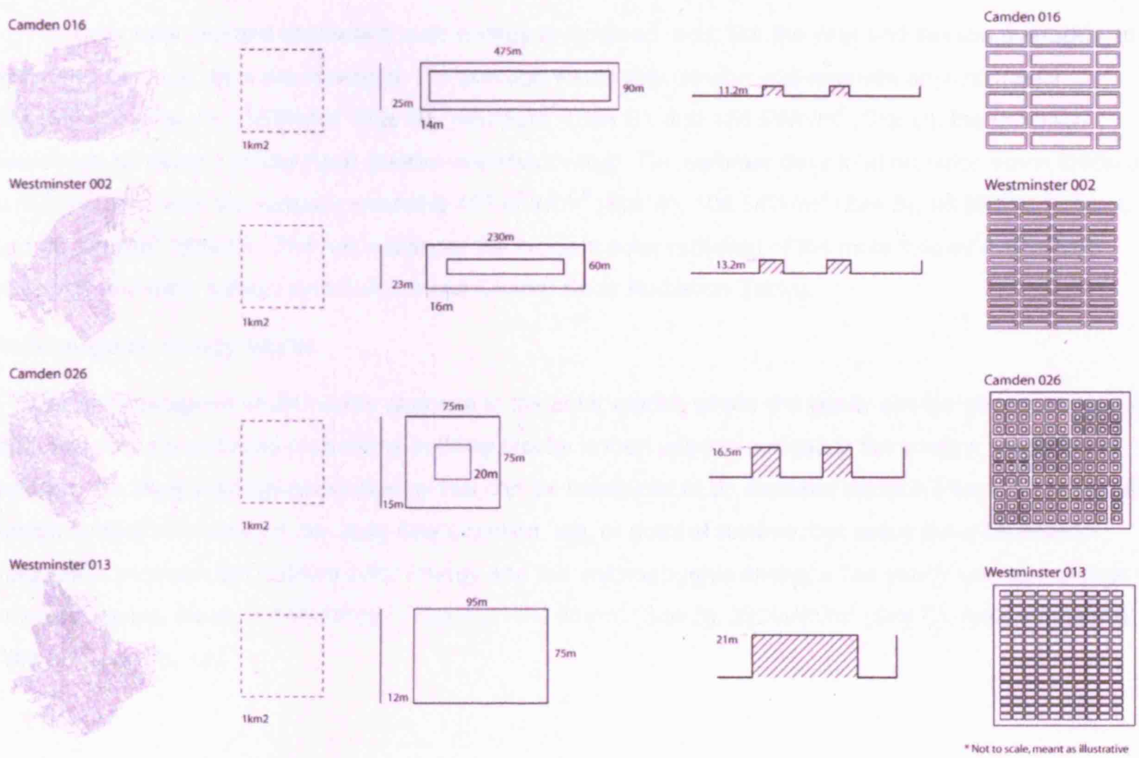
The model of Site C has many small square blocks, which are 75m wide by 75m long and 20m deep. The void within the buildings simulates rear lanes. The width between the building blocks is 15m. The heights of the buildings have all been extruded to 16.5m.

Site D – Very-High Density

The model of Site D also consists of many blocks, which are 75m wide by 95m long. There is no void within the buildings, as the premium of space has required that buildings are very close together. The width between the building blocks is 12m. The heights of the buildings have all been extruded to 21m.

An example of the modeling process is outlined below (see Fig. 17), which illustrates the transformation of the chosen urban environments to a more generic representative form.

Representative Urban Environments Model Transformation*



[Fig. 17: MODEL TRANSFORMATION DIAGRAM]

Solar Energy Model

The SUNtool program calculates the total incident solar radiation for a set of points for each model's exposed building surface. The portion that is measured is a sole activated building form within the center of 8 additional surrounding forms. The calculation provides an energy intensity average per square meter for all the walls (taking into account their orientation), and the roof, for every hour of a year period. The results are assessed for their worst case and average conditions so that an appropriate comparison can be made with anthropogenic energy.

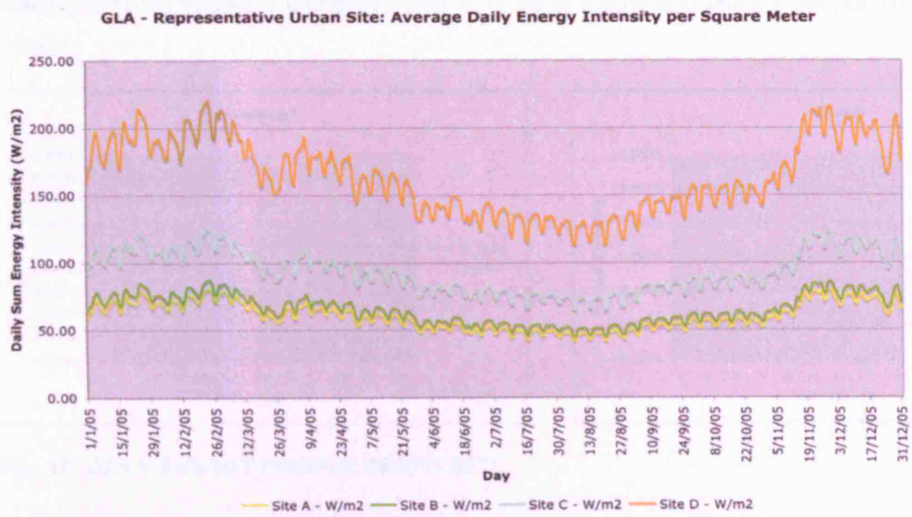
The year average incident shortwave solar radiation on the roof of all the sites was approximately 110W/m^2. Site A (low) experienced the highest average yearly solar energy on the canyon walls at 60.3W/m^2; Site B (medium) experienced radiation of 51.4W/m^2; Site C (high density) experienced 39.6W/m^2; and, Site D (very-high) experienced 37W/m^2. There is a significant difference between sites A to C, but due to the fact site D is not substantially taller than Site C, the total incident year average shortwave solar radiation is not significantly greater.

Beyond the year-average, during the dead of winter, the average daily solar radiations within the canyons are 17.7W/m^2 (Site A), 10.2W/m^2 (Site B), 8.8W/m^2 (Site C), and 6.9W/m^2 (Site D); the roof solar radiation during that time is 19.2W/m^2. The average winter incident solar radiation within the deepest canyons is 1/3rd of that compared to the roof. During the summer, the trend is very similar, with the daily average shortwave solar radiation within the canyons at 119W/m^2 (Site A), 106W/m^2 (Site B), 96W/m^2 (Site C), and 90W/m^2 (Site D); the roof incident solar radiation is 294W/m^2. Again, within the deepest canyon the difference is approximately 1/3rd that of the roof.

The daily total incident shortwave solar energy is summed, and, like the year and season averages, the worst and average days are identified. An average winter day canyon wall receives approximately 423.9Wh/m^2 (Site A), 255Wh/m^2 (Site B), 165Wh/m^2 (Site C), and 158.9Wh/m^2 (Site D); the radiation decreases as denser blocks have greater overshadowing. The summer daily total radiation sums follow a similar pattern, with the canyons receiving 119.66W/m^2 (Site A), 106.54W/m^2 (Site B), 95.95W/m^2 (Site C), and 90.94W/m^2 (Site D). The fluctuation for the incident solar radiation of the roofs follows a standard seasonal and daily pattern (see Graphs and Charts: Solar Radiation Table).

Anthropogenic Energy Model

The anthropogenic model works opposite to the solar model, where the yearly energy values are already identified and the exposed area of the building blocks is then used to normalize the energy. The results illustrate the likely anthropogenic energy that can be measured at an exposed surface area line. Again, the results cannot comment on the likely flow direction, lag, or point of release, but solely the difference in magnitude between the incident solar energy and the anthropogenic energy. The yearly average energy per exposed square meter is 1447Wh/m^2 (Site A), 1562Wh/m^2 (Site B), 2239Wh/m^2 (Site C), and 3930Wh/m^2 (Site D) (see Fig. 18).



[Fig. 18: YEAR-DAILY SUM ENERGY GRAPH]

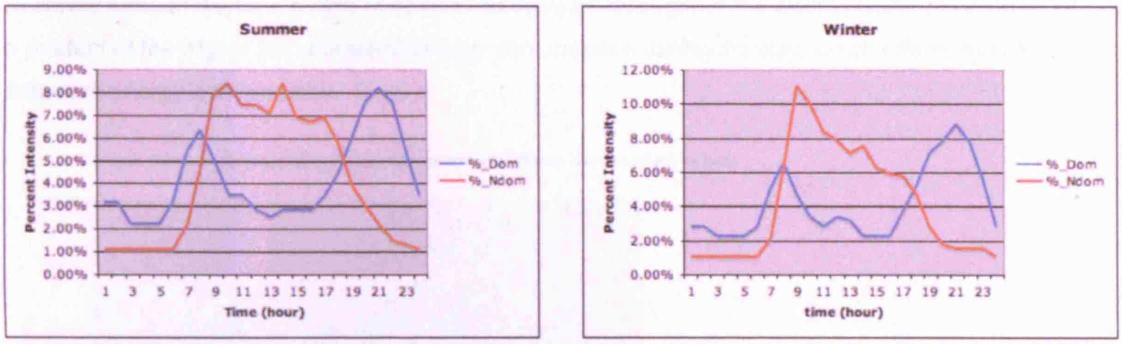
The daily averages during the winter day are 1751W/m^2 (Site A), 1890W/m^2 (Site B), 2709Wh/m^2 (Site C), and 4756Wh/m^2 (Site D). The daily averages during the summer are 1011W/m^2 (Site A), 1172W/m^2 (Site B), 1564Wh/m^2 (Site C), and 2746W/m^2 (Site D). The anthropogenic energy pattern follows a trend opposite to that of the solar energy, as one might suspect, where the summer energy is lowest and winter highest. The anthropogenic radiation output is a function of the exposed surface area within the urban form.

The total daily energy from the solar model can be directly compared to its corresponding model of anthropogenic energy. The two together provide a daily exposed surface energy balance for the representative urban forms within the study area of the GLA. The daily balance comments on the seasonal variation in the balance of the anthropogenic and shortwave solar energy. In order to further examine the trends within a day and the impact on the urban climate, hourly intensities are required for more meaningful results.

6.7 Energy Consumption Patterns

Using the standard energy consumption patterns outlined for UK domestic and non-domestic building types, excluding industrial, the daily energy consumption per unit area within the representative sites is fit to an hourly profile (Q_{Bexp}), which can then be compared to the total incident hourly solar energy (Q_R). The profiles, given as energy percent of each hour , are derived from the whole. The outcome is a profile of the percentage of energy intensity for each sector (see Fig. 19). A profile is derived for typical winter heating and summer cooling; given here is an example of each.

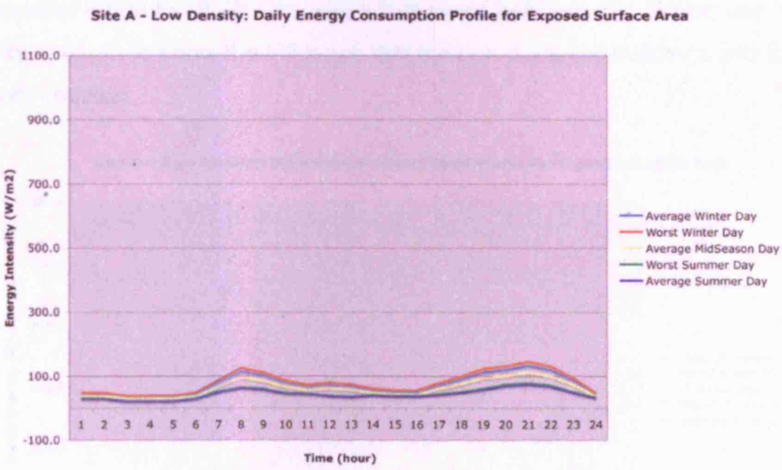
During the heating season the domestic profile is dual-peaked, where at 08:00, 6.55%, and again at 21:00, 8.8%, of the daily total energy is used. During the cooling season, the domestic sector still maintains a dual-peak, however the daytime percentages are slightly higher. The non-domestic sector during the heating season has a single peak in the mid morning at 09:00 of 11.05% that corresponds with morning work hours; it then gradually decreases to 4.74% at 18:00 and drops off to the base load of 1.05%. During the summer cooling period the non-domestic load peaks at 09:00 at 7.87% and fluctuates through the mid day peaking at 13:00 at 8.43% and then again at 17:00 at 6.93% and sharply decreases to the base load of 1.12%.



[Fig. 19: DAILY ENERGY PROFILE GRAPH SET]

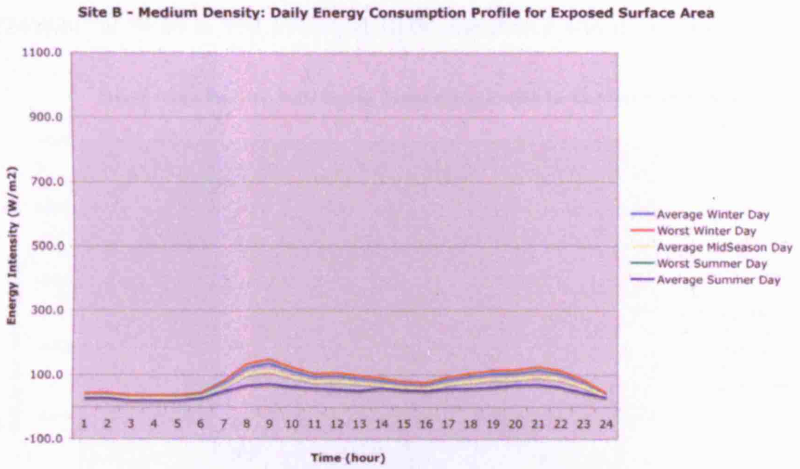
Each representative site's *daily energy consumption* total (GWh) is derived according to its percentage of yearly consumption and is modified to reflect the proportion of domestic and non-domestic energy consumption within the site. This daily energy proportion is then fit to the corresponding daily profile for the particular time of year (summer or winter), which is then divided by the total exposed surface area (m^2).

Site A is predominantly domestic, of which 82.91% of its annual energy is consumed in domestic buildings and 17.09% in the non-domestic. The average hourly profile for Site A reflects its domestic character, which translates into a twin-peaked profile (see Fig. 20). The average winter values range from a base load of 43.9W/m^2 at 01:00 to a peak of 114W/m^2 at 08:00 and 132W/m^2 at 20:00. The midseason ranges from a base load of 36W/m^2 to a peak of 65W/m^2 at 10:00 and then peaks again at 21:00 at 110W/m^2. During the summer Site A still maintains a dual-peak, but slightly reduced with a morning peak of 61W/m^2 at 08:00 a drop at 13:00 to 33W/m^2 and another peak at 09:00 of 72W/m^2.



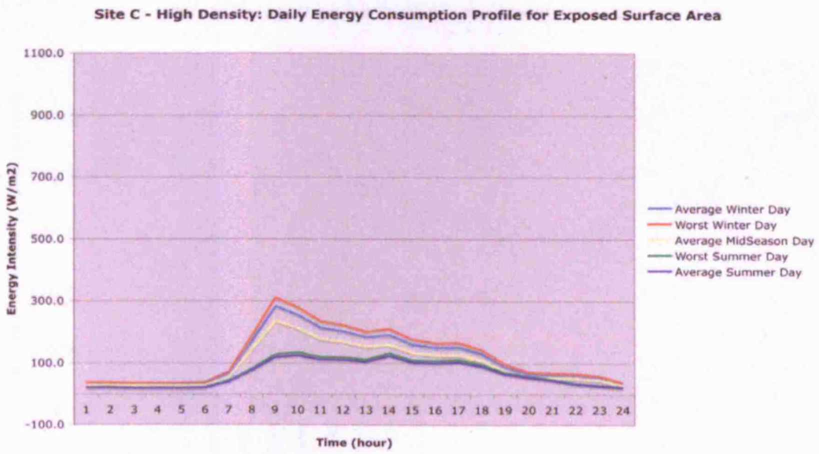
[Fig. 20: YEAR SITE A PROFILE]

The profile of Site B has a greater mix than that of Site A, with 61.4% and 38.6% of the energy consumed by the domestic and non-domestic sectors respectively; the outcome is a less defined dual-peaked profile (see Fig. 21). During the winter the peak energy intensity is 135W/m^2 at 09:00, decreases to 69W/m^2 at 16:00, peaks again at 20:00 with 113W/m^2, and then decreases to the base load of 54W/m^2. The midseason profile shows a base load of 33W/m^2 with peaks in the morning and late evening with energy intensities of 112W/m^2 and 94W/m^2 and a late afternoon value of 60W/m^2. The summer profile for site B maintains a relatively smooth daytime profile of 48W/m^2 to 68W/m^2 throughout the waking hours of 08:00-21:00, which is a product of the higher non-domestic energy consumption during the day, which offsets the attenuation of domestic energy consumption.



[Fig. 21: YEAR SITE B PROFILE]

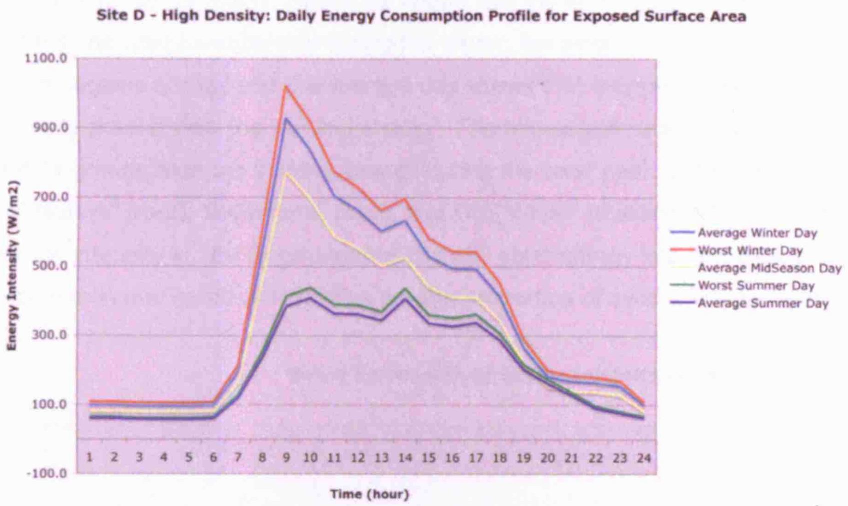
Site C is predominantly non-domestic with a few domestic buildings, which consume 90.33% and 9.67%of the energy respectively. The average daily winter profile has a peak of 282.7W/m^2 at 09:00, a gradual decrease to 151.5W/m^2 at 17:00, and then a drop to the base load of 33.1W/m^2. The midseason has a similar single peak profile (see Fig. 22) with a peak energy intensity of 235.2W/m^2 at 09:00 and then a gradual decrease to the base load of 27.6W/m^2. The summer profile is relatively smooth during the working hours of 09:00 to 18:00 with values that range between 124.3W/m^2 and 88.7W/m^2[32]. The energy profiles of Site C begin to show the influence that the non-domestic buildings and their work schedule has on energy consumption.



[Fig. 22: YEAR SITE C PROFILE]

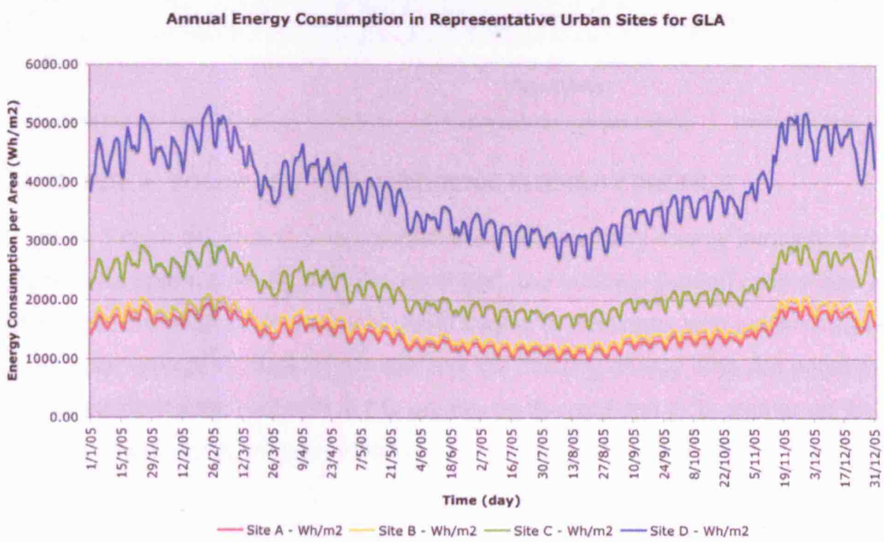
[32] The smooth energy profile consumed during these hours can likely be attributed to air conditioning units as the 13:00 spike to 75W/m2 might suggest.

In comparison, Site D consumption consists of 4.9% domestic and 95.1% non-domestic energy. The average winter profile for this site is dominated by the non-domestic consumption, which creates a single peak (see Fig. 23) in the late morning of 510W/m^2 at 09:00 and a decrease to 226W/m^2 at 17:00 and then a sharp decline to the base load of 54.2W/m^2. The midseason profile indicates a steep peak in the morning at 09:00 with 424W/m^2, a gradual decline through the working hours until 18:00 with 188W/m^2, then a drop to the base load of 45.1W/m^2. The summer profile shows only a slight decrease during the day from a peak of 224W/m^2 at 10:00 to 157.5W/m^2 at 18:00 and then a sharp decline to the base load of 33.7W/m^2.



[Fig. 23: YEAR SITE D PROFILE]

The above are 'average' and 'worst-case' daily energy totals, extracted from the daily UK gas and electricity energy totals. Again, due to local variations in temperatures the exact date of these scenarios are not exact, and the results must be taken as indicative of the likely energy intensity profile through the day within the representative sites. The Graph (see Fig. 24) below shows the different seasonal scenarios for Sites A-D.

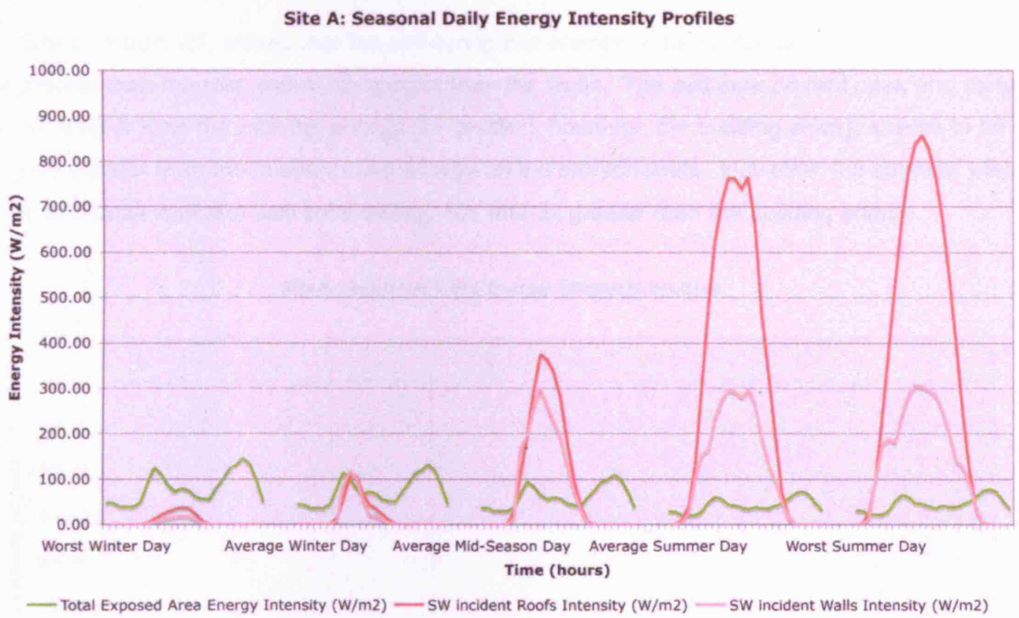


[Fig. 24: REPRESENTATIVE SITES SEASONAL DAILY PROFILES]

6.8 Exposed Surface Energy Balance

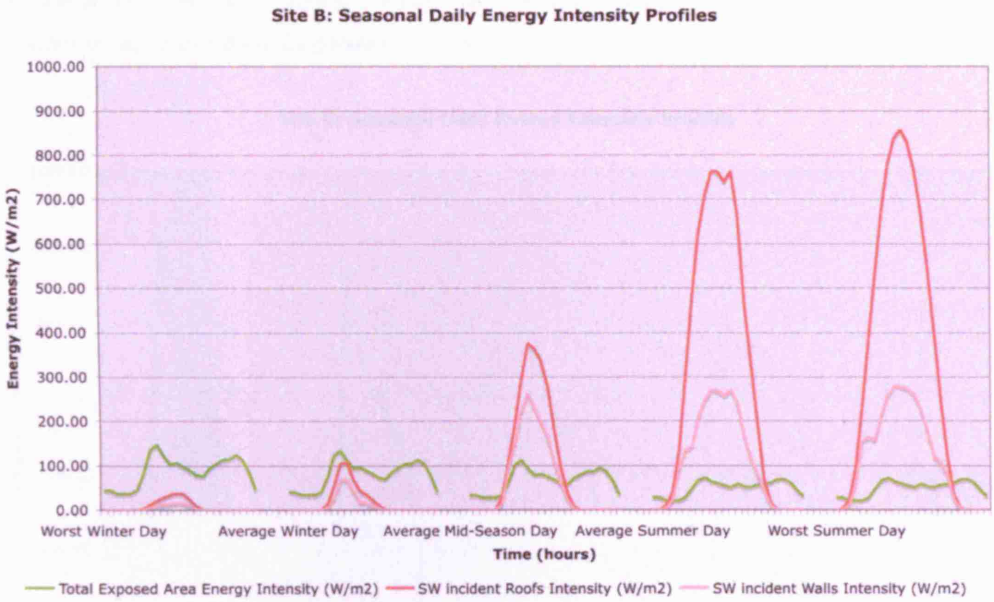
The total incident shortwave solar radiation per unit area (Q_R) results from the solar modeling can be compared to the estimated hourly anthropogenic energy intensity per unity area (Q_{Bexp}) of the representative urban environments within the study area of the GLA. The outcome is a set of energy balances for selected average and worst-case scenario days for each site (see Charts and Graphs: Hourly Solar & Anthropogenic Energy Profiles).

The balance for Site A, Figure 25, shows that the anthropogenic energy is dominant on the wall and roof surface line area balance only during the winter; the worst-case day shows lower solar radiation than anthropogenic energy and the average day shows that only during the morning 09:00-10:00 is solar energy intensity greater than the building energy. The mid-season average roof and wall solar energy intensity is 2x and 1x greater than the building energy during the solar peak, but is very close to the daily sum with 2304Wh/m^2 (roof), 1849Wh/m^2 (wall), and 1457Wh/m^2 (building). During the summer, the peak roof solar energy intensity is 18-20x greater and the wall solar energy intensity 6-8x greater. The daily sums for the mid-season and summer indicate a greater proportion of available solar energy than building consumption.



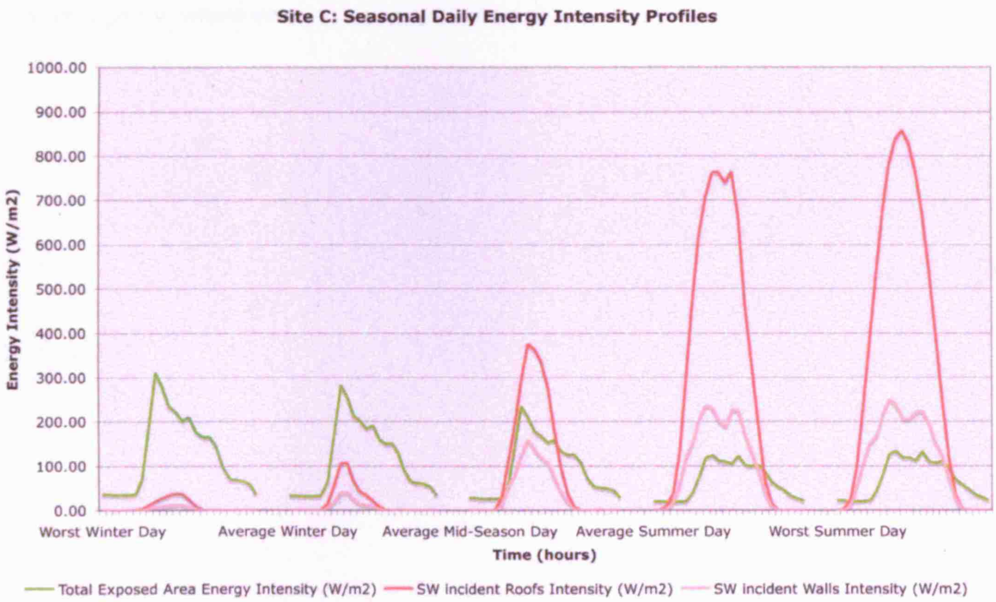
[FIG. 25: SITE A: SOLAR AND ANTHROPOGENIC INTENSITY PROFILE]

Site B, Figure 26, shows a very similar trend with building energy intensity dominating the exposed surface area balance during both the worst (2x) and average (equal) case winter days. During the midseason, the peak solar energy intensity begins to dominate, with walls 1x and roof 2x; however, the daily sum of solar energy incident on the wall and the building energy area are equal at ~1500Wh/m^2. The peak summer incident solar radiation is 14x greater on the roof and 4-5x greater on the walls; the daily sum is also far greater than built form consumption.



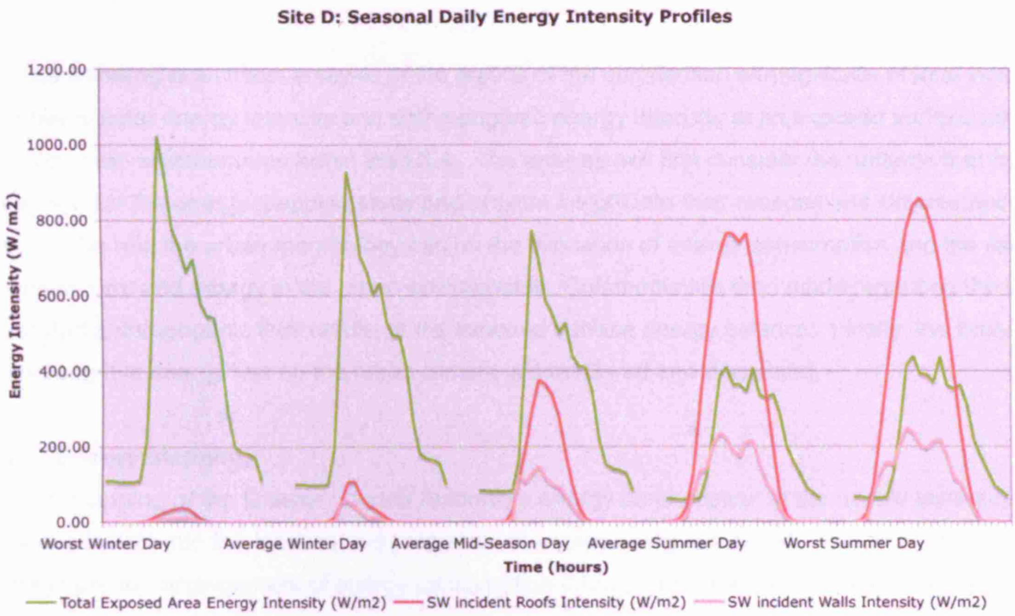
[FIG. 26: SITE B: SOLAR AND ANTHROPOGENIC INTENSITY PROFILE]

Site C, Figure 27, shows that the anthropogenic energy is the dominant component during the winter: 1-4x greater than the roof and 4-12x greater than the walls. The mid-season roof peak and daily solar energy is still greater than the building energy (2x greater); however, the building energy seems to be equal or slightly greater than the incident solar energy on the canyon walls. However, the summer period shows a daily and peak roof and wall solar energy 10x and 2x greater than the building energy.



[FIG. 27: SITE C: SOLAR AND ANTHROPOGENIC INTENSITY PROFILE]

Site D, Figure 28, shows that built form energy dominates the wall surface energy balance through the whole year and ranges between 10-42x greater during the winter and 1.5-2x greater during the summer. The daily totals are the same, with the building energy consistently requiring more energy than is incident from the sun on the walls. During the summer, the solar energy intensity on the roof is still the dominant component, approximately 2x greater.



[FIG. 28: SITE D: SOLAR AND ANTHROPOGENIC INTENSITY PROFILE]

The results indicate that the building energy consumption is greater than the incident solar radiation during the winter in all sites; and, that in the very high density sites that consume large quantities of anthropogenic energy, the building energy will be the dominant component of the surface energy on the walls through the whole year.

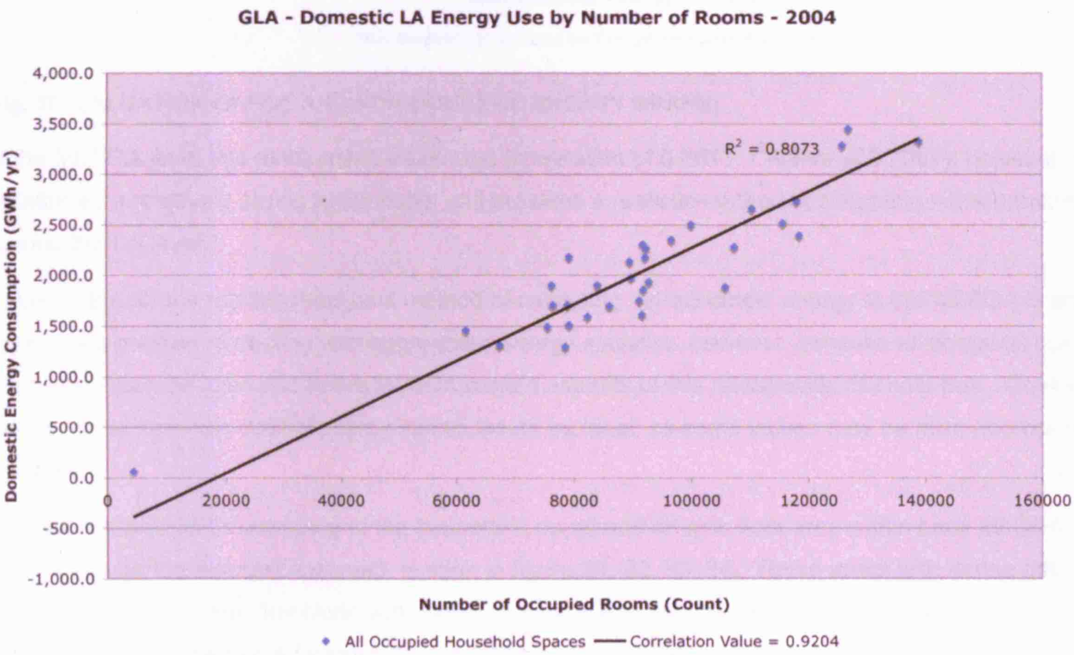
7.0 Analysis

The following is a critical analysis of the results of the comparison of magnitude of total incident shortwave solar energy intensity and anthropogenic energy intensity at an exposed surface area line in varying urban environments within the GLA. The analysis will first consider the patterns that have emerged as a result of the energy mapping study and provide insight into their reasons and circumstances. It will then discuss the role the urban morphology has on the allocation of energy consumption and the relationships between form and energy in the urban environment. Comments are then made regarding the comparison of solar and anthropogenic final results of the exposed surface energy balance. Finally, the likely impact that anthropogenic energy has on the urban climate is considered and discussed.

7.1 Energy mapping

The mapping of the Greater London Authority's energy consumption at the middle layer super output area provides insight into the location and proportion of energy being consumed. The most striking patterns to emerge are the arrangement of energy consumption through the GLA, and its relationship with the domestic and non-domestic building sectors.

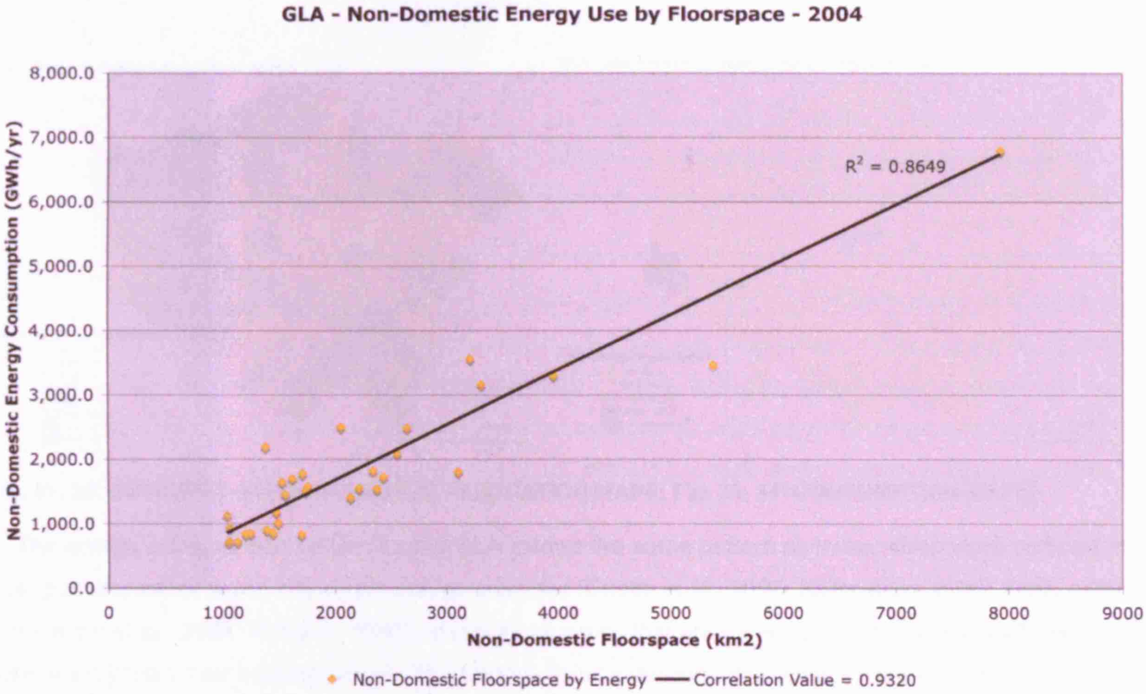
At the local authority level a relationship between domestic energy use and occupied household size is established using 2001 ONS occupied household spaces census data for local authorities and local authority level energy consumption (see Fig. 29). The outcome indicates a strong relationship (a correlation of 0.9204; r^2-value of 0.8073) between the occupied spaces and domestic energy consumption, where those authorities that had high numbers and larger households consumed a larger portion of domestic energy.



[Fig. 29: HOUSEHOLD COUNT AND DOMESTIC ENERGY GRAPH]

If the household spaces were ranked according to those households, with more occupied spaces consuming more than a single household space, then the relationship was even stronger (correlation of 0.9833). The relationship, once at the MLSOA level, weakens (correlation of 0.4714) for the unranked spaces but remains relatively strong for the ranked values (correlation 0.8908); the reason is likely due to the issue of the clustering of larger domestic consumers in addition to total counts.

The analysis for the non-domestic energy used Valuation Office rateable floorspace data for 4 bulk class types (office, retail, warehouse, and industrial) and established a strong relationship (see Fig. 30) between LA level energy consumption and floorspace area (correlation of 0.9320; r^2-value of 0.8649).

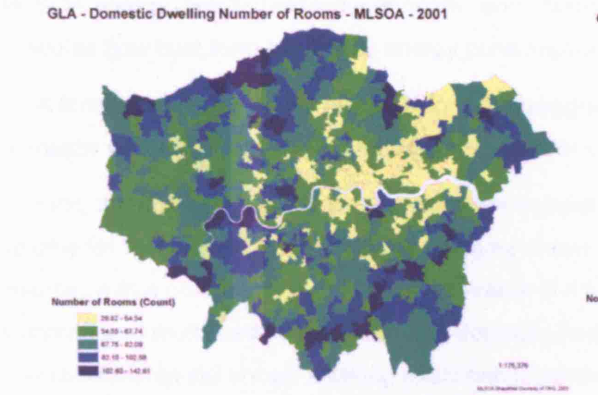


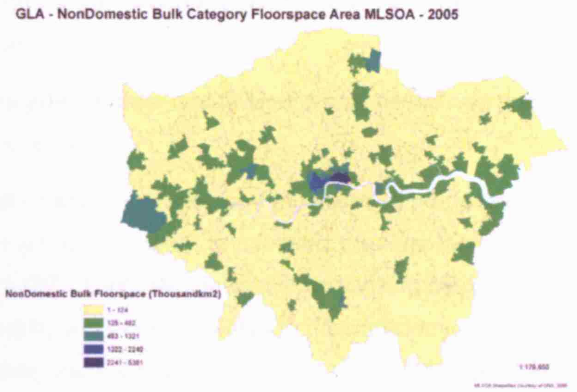
[Fig. 30: VALUATION OFFICE AND NON-DOMESTIC ENERGY GRAPH]

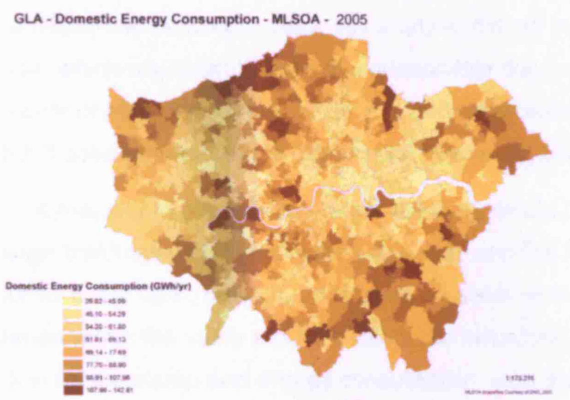
At the MLSOA level this relationship weakened (correlation of 0.8613; r^2-value of 0.7067); however, it still maintained a relatively strong relationship and provides a realistic method of allocating non-domestic energy beyond the LA level.

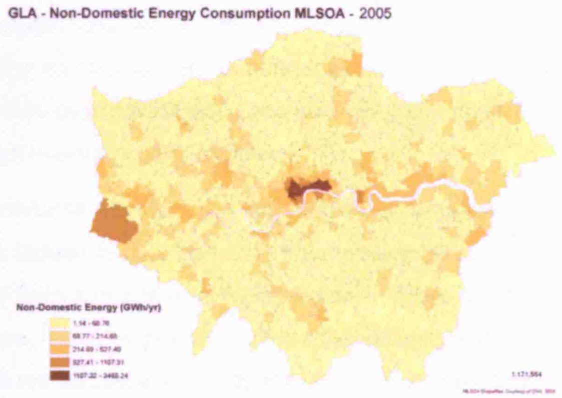
Using the above relationships as a method of assigning 'un-allocated' energy to the MLSOA is an appropriate method of dealing with aggregated energy statistics, however, because all domestic gas and electricity data was allocated to the MLSOA certain aspects of this relationship still hold true. Obviously, having higher resolved spatial energy values would be ideal, as some values may be miss-appropriately assigned

A progression of the mapping of the household count and all-bulk floor area within each MLSOA, and the effect it has on the energy consumed, is seen in figure 31, 32, 33, 34. Those areas with dense office, retail and industrial areas are very clear, with high consumption in the City of London, Heathrow Airport, central Westminster, Bloomsbury & Holborn, Canary Wharf and several large business parks throughout outer London. These are all areas that are known to have high amounts of non-domestic operations.









[Fig. 31, 32: DOMESTIC & NON-DOMESTOC ALLOCATION MAPS; Fig. 33, 34: CONSUMPTION MAPS]

The energy consumption pattern for the GLA follows the same pattern as those which were outlined of other post-industrial urban city center energy analyses [Coutts et al., 2007; Sailor & Lu, 2004; Taha, 1997; Yamaguchi et al., 2004; Klysik K, 1996], where those areas that are more built up and dense, will consume more energy than their outlying areas. This pattern helps establish the intensive nature of urban environments; that they consume beyond their own abilities to passively sustain their needs of the built form, creating a net negative balance in energy use.

7.2 Morphology and Energy Allocation

The relationship between urban form and the consumption of energy has proven to be significant in this study. The use of household data and valuation office floor area was helpful in allocating energy beyond the local authority level; however, a further analysis helps indicate how the *shape* of the urban form influences energy consumption. The following is in response to a reference made by Ratti et al. [2005], who hinted at the multi-variable nature of energy consumption and urban morphology.

The study made use of energy that was largely allocated to the MLSOA by the DTI, in which there was a very strong relationship (correlation of 0.9893, r^2 value of 0.9788) between the size of total building volume and the consumption of energy within the MLSOA. The two variables used in this analysis, volume and

MLSOA energy, are derived independently, and, though the sample contains only 43 sites[33], the relationship indicates how built form influences energy consumption.

A further validation of this relationship is to disaggregate the data and assess the domestic and non-domestic volume and its related MLSOA energy consumption.

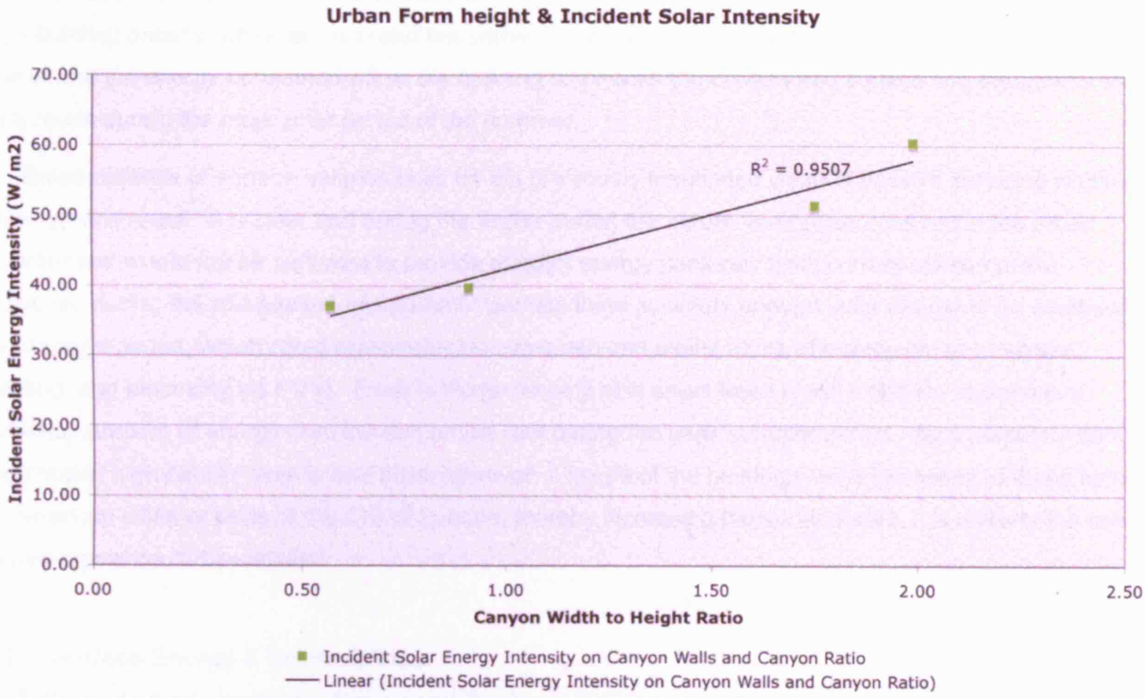
First, the domestic area is summed and the domestic height averaged and multiplied to produce domestic volume for the selected MLSOA's; the outcome shows a slightly weaker relationship than the total building volume, with a correlation of 0.7554 and r^2-value of 0.5707. Then, all non-domestic building sector area is summed and multiplied by the mean non-domestic height, and then correlated to the non-domestic energy. The relationship still shows a strong relationship between volume and energy, with a correlation of 0.9802 and an r^2-value of 0.9608. It is possible that the domestic volume and energy are not as strongly related due to mixed-use buildings. Also, this analysis did not include those areas with large proportions of industrial use, which would likely skew this relationship due to the inability to class industrial consumption by building shape or size [Steadman, 1979]; this cannot be validated beyond domestic and non-industrial applications, but it does emphasize the importance that height plays in energy consumption.

It may seem obvious that larger buildings would consume more energy, and that those areas with more large buildings would follow the same rule, and this is indeed largely true within post-industrialized urban forms in the GLA; however, it is worth considering the links it draws beyond fabric form. Since most of the areas within the study site held little to no industrial use, it can be plausibly stated that urban volume has a direct relationship with energy consumption; and, that the variance in floorspace intensity of individual properties can be aggregate, and the output provide a realistic portrayal of the anthropogenic ergomorphic nature of the built form.

7.3 Canyon Ratio & Energy

Another aspect of urban morphology that indicates a relationship is the canyon width to height ratio (canyon ratio) and the energy consumed within the surrounding buildings. A brief assessment of the urban canyon ratios in representative sites indicates that those areas with deep canyons will receive the least amount of solar radiation (see Fig. 35). This relationship is relatively straightforward, as deeper canyons are subject to more overshadowing, thus reducing the amount of incident solar radiation on the canyon walls. However, when the canyon ratio and the annual energy consumption values are assessed a second relationship is revealed. It is shown that, as the canyons increase, so does the energy consumed by the surrounding buildings.

[33] Due to the limitations in availability of the whole NLUD database for the GLA only those sites within the study area could be tested for this relationship.



[Fig. 35: CANYON RATIO & ENERGY – SOLAR AND ANTHROPOGENIC]

Again, this relationship is hinged on the fact that there is little to no industrial building use within the sites and is weakened simply due to the limited number of test samples.

The clustering of buildings into dense urban forms shows that there is an increase in anthropogenic energy consumption. These areas will suffer from reduced incident solar radiation on the walls within the canyon, as overshadowing is increased with height. The roof captures the largest proportion of shortwave radiation and, if all buildings are of a relatively equal height and do not receive any overshadowing, the incident solar radiation fluctuates according to seasonal patterns. As urban forms reach greater heights and density, and as the volume and energy analysis have indicated, consume more energy, they will be subject to lower levels of solar energy, thus decreasing the building floor area that can be passively serviced [Steadman et al., 2000].

7.4 Surface Energy Balance

The comparison between the total incident solar radiation and the anthropogenic energy intensity for an exposed surface area line within varying urban forms within the GLA, has indicated how the surface balance is not solely dominated by the sun and is infact opposite in dense urban areas.

The pattern that has emerged is that low-density areas, which are predominantly made of domestic buildings, consume the least amount of anthropogenic energy. In addition, these low-density areas also have the least volume in comparison to open-area. The outcome is a pattern that shows how building energy will dominate wall and roof area during the winter, and the solar energy will dominate during the summer. This trend is also true for the medium and high density areas, the difference being the amount of energy consumed by the buildings and the incident solar energy in the deeper canyon walls.

This pattern changes in urban areas that are subject to very high anthropogenic energy consumption and high building density, which are one and the same in post-industrial urban forms. The trend in these areas is one where the energy consumed within the building dominates the canyon wall surface line throughout the year, even during the peak solar period of the summer.

These patterns of surface balance build on the previously mentioned issue of passive servicing within the urban environment. It is clear that during the winter period the natural energy sources within the urban environment would not be sufficient to provide enough energy passively (with current consumption). However, during the mid-season and summer periods there is clearly enough solar energy to be used during the daylight period, which could reasonably be converted into useful forms of energy (solar hot-water heating, and electricity via PV's). Even in those densely built areas there is still a chance to provide a sufficient amount of energy from the sun on the roof during the peak summer period. Approximately 60% of the chosen high density area is roof area; however, if height of the buildings were increased to those similar to American cities or parts of the City of London, thereby increasing the surface area, it is unlikely the energy requirements could be satisfied.

7.5 Surface Energy & Urban Climate

A study of urban climate by Harman and Belcher [2006] indicated the strong relationship between the fraction of roof area and the strength of the sensible-heat flux to the boundary layer over urban street canyons, which in effect means that the roof area has a significant influence over the temperature of the urban boundary. The study also indicated the urban canyons sensible-heat flux to the boundary layer is limited and that this flux from the canyon is "not strongly sensitive to canyon geometry". Larger canyons with greater surface area have increased flux to the layer, however, the surrounding buildings will reduce that flux. It could be suggested from their results that the surface energy within an urban canyon will have a greater effect on the canyon than on the boundary layer and that the roof surface energy will have a considerable effect on the boundary layer.

The above study used a set indoor temperature to simulate the likely indoor environment. However, the results of this study, which use known energy consumption statistics, can be used to indicate the likely heat flux that anthropogenic energy use will have on the urban climate, providing fabric parameters were applied to this study's values.

As an example, in Site A, the low density area, approximately 70% of exposed surface area is roof area. The energy ranges between an average of 42W/m^2 during the summer and 73W/m^2 during the winter a daily total 1751.6Wh/m^2, which could potentially be released via the roof. During the summer, the average building energy consumption is 0.24GWh/day, if proportioned to area, the building energy at the walls would be 0.11GWh/day and 0.13GWh/day at the roof. The solar energy within that same area would be approximately 0.53GWh/day incident on the walls and 0.90GWh/day on the roof. Ignoring fabric lag, the sum of the energy could see the canyon environment receive 0.64GWh/day; the roof could release upwards of 1.03GWh/day directly to the boundary layer. During the winter, the roof could release 0.22GWh/day to the urban canyon environment and 0.28GWh/day to the boundary layer via the walls and roof respectively.

In higher density areas like Site D, the roof area is approximately 60% of its exposed surface area, in which case the building energy release ranges from 198W/m^2 in the winter and 114W/m^2 during the summer.

During the summer the total average daily energy consumed within that area is 4.1GWh/day, of which the energy at the walls is 2.05GWh/day and 2.05GWh/day at the roof. The solar energy during that time is 1.6GWh/day incident on the walls and 5.35GWh/day on the roof. Combined, the release to the urban canyon could be up to 3.72GWh/day, and 7.43GWh/day could be released directly to the boundary layer via the roofs. During the winter, the same combined release could be 3.75GWh/day and 3.95GWh/day via the walls and roofs respectively.

In both environments, the anthropogenic energy accounts for a significant amount of the energy balance. The total amount of anthropogenic energy potentially released towards urban canyon environments and directly to the urban boundary layer in the GLA is significant. The energy intensity values experienced within the GLA are closer to those established by Taha [1997], than Ichinose [1999], but still indicate a likely influence on urban temperatures. A study of the GLA's urban heat island phenomena indicates that the center of the island sits above the Old street and Farringdon Rd area within the City of London [Watkins et al., 2002]. In addition to the large amount of exposed surface area found in that area, the site consumes a huge amount of anthropogenic energy, 3500GWh/yr. The total solar energy incident on the walls and roofs would be 3026GWh/yr[34]. This indicates that anthropogenic energy could be equal to or greater than the solar energy within the City of London, a substantial difference that would certainly affect the urban environment, and likely exacerbate urban climate phenomena like the urban heat island. The implication of this large proportion of energy is briefly shown in the LAQN temperature data comparison between rural sites and central London, where a 5K temperature difference persisted year-round.

The Taha [1997] study of several large world cities concluded that the sensible urban environment, with its lack of green space and dark surfaces would be greatly impacted by large city center heat release due to anthropogenic heating. So, in addition to increasing surface albedo to reduce solar absorption [Bonan, 2002; McKendry 2003] and increasing green spaces within the urban centers [Upmanis et al., 1998], decreasing the energy consumption within the built form of the GLA will likely help reduce the overall UHI.

[34] The area of the City of London is 3.14km2, the average yearly solar energy incident on a meter square is 110W/m2, the daily average incident solar energy is 2640Wh/m2, and the estimated annual total energy is 9.64×10^4GWh/m2.

8.0 Summary

The outcome of the study indicates that the highest proportion of annual energy consumed within the built form of the GLA is concentrated in central London and scattered areas around outer London. The pattern follows the concentration of domestic and non-domestic operations, their clustering, and the density of the urban form. The pattern established indicates that low-density areas are typically low-rise (<9m), predominantly domestic (80%+ building count and area), and consume the least amount of energy (0-144kWh/m^2); that medium and high density areas are of varying height (9-21m), predominantly mixed (40-60% domestic and non-domestic), and consume a varying amount of energy (146-455kWh/m^2); and, that the very high density areas, with high to high-rise heights (21m+, average 35m), are predominantly non-domestic (80%+), and consume a large amount of energy (456+kWh/m^2).

The second portion of the study shows that the daily exposed surface (wall and roof) energy balance within all representative urban environments is dominated by anthropogenic energy during the winter (5-20% solar); that during the mid-season the solar and building energy intensity is dependant on density, with less dense areas dominated by solar (60%) and more dense areas dominated by the building (20% solar); that during the summer, solar energy becomes the dominant energy form within the low to high density areas (85-70% solar); and, that during an average summer day the roof surface of the very high density area is dominated by the solar energy (70% solar), but, the anthropogenic energy dominates the canyon surfaces (40% solar). The profiling of the energy intensity indicates that areas largely made up of domestic buildings tend to peak during the morning and evening, where areas with largely non-domestic (excluding industrial) operations tend to peak during the mid morning and decrease throughout the day; and, that during any particular point of the day the balance of energy is influenced by the likely energy use within the urban form and the urban form itself.

In terms of climatology for the GLA and south-east England, the study's 1km^2 output grid of energy consumption by the built form within the GLA can easily be placed in climate models of similar resolution; this energy can be used, along with transport, as the anthropogenic heat flux (Q_F) in the urban surface energy balance equation. The values could provide important insight into the impact that large urban centers have on micro, citywide and regional climate, particularly temperatures.

Policy makers for the GLA should also find this study helpful for several reasons. (1) The link drawn between the energy consumed within high density areas of the GLA and the implications to the urban climate are very important. It indicates that developments within those areas <u>must</u> reduce their consumption in order to lessen the effect anthropogenic energy has on the urban heat island. (2) It also means that increasing the density within the core will have a significant impact on the solar and anthropogenic energy balance; the 1km^2 energy values can be used as a means of limiting energy intensive developments. In order to encourage development in less dense areas a levy system, similar to the congestion charge zone, could be applied to those areas with very high anthropogenic energy consumption. Businesses who choose to locate in the center could be required to retrofit to less energy intensive systems and reduce their energy use to avoid the fee; the same system could be applied to new building developments.

The study is able to provide highly resolved temporal and spatial scale energy consumption values for the GLA; this knowledge of the likely energy consumption pattern at an hourly scale allows for an assessment of the application of renewable and district energy systems within urban areas of the GLA by identifying the potential base loads that can be used for particular energy technologies. In addition, the anthropogenic energy values for each MLSOA can easily be translated into CO_2, as the makeup of the energy fuels is known, which means specific targets can be set for CO_2 emission reductions in the MLSOA's, helping to meet the UK's 60% emissions cut by 2050 (DTI, 2003).

9.0 Conclusion

The study quantified anthropogenic energy consumption for the GLA at an appropriate temporal and spatial scale; then, it rationalized the quantified energy consumption for representative urban environments for the GLA that considered their morphology and typology; finally, the total incident shortwave solar energy and anthropogenic energy was modeled within the representative sites and fit to a daily profile that described the exposed surface energy balance.

The outcome of the project shows where areas of low, medium, high and very high energy consumption occur within the GLA. The results also identify an exponential energy consumption pattern within the city, with 75% of MLSOA's annually consuming less than 143kWh/m^2, 19% consuming between 144-260kWh/m^2, 5% consuming between 261-700kWh/m^2, and only 1% consuming above 700kWh/m^2; the pattern creates a concentric distribution radiating from the city center. The study also illustrates that low-rise, low density areas generally consume low amounts of anthropogenic energy with a high percentage of domestic buildings, and that high-rise, high density areas generally consume high amounts of anthropogenic energy with a high percentage of non-domestic buildings.

The study also shows how incident shortwave solar energy will dominate the exposed surface energy balance on the roofs and urban canyons in areas with low density and wide streets during the mid-season and summer; but, that the anthropogenic energy dominates all surfaces during the winter. However, in high-density, deep canyon sites the solar energy maintains its dominance on the roof surface but anthropogenic energy dominates the canyon surface energy balance through the whole year.

The use of several key pieces of information was found to be significant through the study. Using morphology in the study of energy consumption within urban environment helps to further rationalize and validate energy allocation; and, that building volume is a very good indicator of post-industrial urban energy consumption. Also, the use of typology helps to identify and link a pattern between building type and morphology; that generally low-density areas are predominantly domestic, and that high-density areas are predominantly non-domestic or highly mixed.

Quantifying, rationalizing and comparing the solar and anthropogenic energy incident within varying urban environments of the GLA allows one to make further links with other urban studies. It is believed that in those urban areas with deep canyons and high-density, the anthropogenic energy will contribute a significant portion of energy directly to the boundary layer and to the urban climate environment. A link is also made between urban heat island phenomena and areas of high density and high anthropogenic energy, indicating the importance that human-used energy has on the formation and possible mitigation of the urban heat island.

Finally, the study helps to define the ergomorphic structure of the built form within the GLA during different times of the year in varying urban environments. It provides knowledge of the dominant energy sources that occur within these environments, which can be associated to likely influences on the urban climate. The ergomorphic structure of the urban environment can be used to illustrate its effect on the local and meso scale environment and can provide information on the 'passive' abilities of current urban forms.

Works Cited

Arnfield A J, *Two decades of urban climate research: A review of turbulance, exhanges of energy and water, and the urban heat island*, International Journal of Climatology, Vol. 23, pp. 1-26, Royal Meteorological Society, Wiley Interscience, 2003.

Bonan G, *Urban ecosystems*. Chapter 14 in Ecological Climatology Concepts and Applications. Cambridge University Press, pp. 574-586, 2002

Bridgeman H A, Oliver J E, *The Global Climate System: Patterns, Processes, and Teleconnections*, Chapter 7, Cambridge University Press, 2006.

Brown F E, Rickaby P A, Bruhns H R, Steadman J P, *Surveys of nondomestic buildings in four English towns*, Environment and Planning B: Planning and Design, Vol. 27, pp. 11-24, Pion Publications, Great Britain, 2000.

Cities Revealed, *Product Information: City Heights*, The Geoinformation Group Ltd, Cambridge, UK, 2004, Website: www.citiesrevealed.com, Accessed June, 2007.

Coutts A M, Beringer J, Tapper N J, *Impact of Increasing Urban Density on Local Climate: Spatial and Temporal Variations in the Surface Energy Balance in Melbourne, Australia*, Journal of Applied Meteorology, Vol. 46, pp 477-493, American Meteorological Society, 2007.

DTI, *Energy White Paper*, Department of Trade and Industry, Webpage: http://www.dti.gov.uk/energy/whitepaper/index.shtml, Accessed: August 2007.

DTI, *Regional Energy Consumption Statistics*, Webpage: http://www.dti.gov.uk/energy/statistics/regional/index.html Accessed: February 2007

DTI, *DTI Middle Layer Super Output Area Electricity Consumption Analysis*, Department of Trade and Industry, December 22, 2006a.

DTI, *Guidance note to assist local Authorities to Interpret The DTI sub national energy consumption statistics*, Department of Trade and Industry, December 22, 2006b.

GEO, *Global Environmental Outlook 2003*, United Nations Environment Programme, Geneva, www.unep.org/GEO/geo3, 2003

Givoni B, *Comfort, climate analysis and building design guidelines*, Energy and Buildings, Vol. 18, pp. 11-23, Elsevier Sequoia, 1992.

Grimmond C S B, *Variability of urban climates*, Essay in Bridgeman & Oliver The Global Climate System: Patterns, Processes, and Teleconnections, Chapter 7, Cambridge University Press, 2006.

Grimmond C S B, Oke T, *Turbulant Heat Fluxes in Urban Areas: Observations and a Local-Scale Urban Meteorological Parameterization Scheme (LUMPS)*, Journal of Applied Meteorology, Vol. 41, Issue 7, pp 792-810, American Meteorological Society, 2002.

Harrison R, McGoldrick B, Williams C G B, *Artificial Heat Release from Greater London, 1971-1976*, Atmospheric Environment, Vol. 18, No. 11, pp. 2291-2304, Pergamon Press Ltd., 1984

Harman I N, *The Energy Balance of Urban Areas*, PhD Thesis, University of Reading, Department of Meteorology, October 2003.

Harman I N, Belcher S E, *The surface energy balance and boundary layer over urban street canyons*, Quarterly Journal of the Royal Meteorological Society, Vol. 132, pp. 2749-2768, Royal Meteorological Society, 2006.

Ichinose T, Shimodozono K, Hanaki K, *Impact of anthropogenic heat on urban climate in Tokyo*, Atmospheric Environment, Vol. 33, pp. 3897-3909, Pergamon, Elsevier Sciences Ltd., 1999.

Kimura F, Takahashi S, *The effect of land use and anthropogenic heating on the surface temperatures in the Tokyo Metropolitan Area: A numerical experiment*, Atmospheric Environment, Vol. 25B, No. 2, pp. 155-164, Elsevier Science Ltd., 1991.

Klysik K, *Spatial and Seasonal distribution of anthropogenic heat emissions in Lodz, Poland*, Atmospheric Environment, Vol. 30, No. 20, pp. 3397-3404, Elsevier Science Ltd. 1996.

MOL, *London's Urban Heat Island: A Summary for Decision Makers*, Greater London Authority, City Hall, London, October 2006.

MOL, *The London Plan, Spatial Development Strategy for Greater London*, Greater London Authority, City Hall, London, February 2004.

MOL, *London Energy and CO2 Emissions Inventory 2003: Methodology Manual*, Greater London Authority, City Hall, London, April 2006.

MOL, *Green light to clean power: The Mayor's energy strategy*, Greater London Authority, City Hall, London, February, 2004.

NOMIS, *Labour Market Profile: Inner London*, Office labour market statistics, Office of National Statistics, Her Majesty's Stationery Office, Users license: C2007001656, Crown Copyright, 2007.

Mortimer N D, Elsayed M A, Grant J F, *Patterns of energy use in nondomestic buildings*, Environment and Planning B: Planning and Design, Vol. 27, pp. 709-720, Pion Publications, Great Britain, 2000.

Robinson D, *Urban Morhpology and Indicators of radiation availability*, Solar Energy, Vol. 80, pp. 1643-1648, Elsevier Ltd., 2006.

Robinson D, Stone A, *Solar Radiation modeling in the urban context*, Solar Energy, Vol. 77, pp. 295-309, Elsevier Science Ltd., 2004.

Ratti C, Baker N, Steemers K, *Energy consumption and urban texture*, Energy and Buildings, Vol. 37, pp. 762-776, Elsevier B.V., 2005.

Sailor D, Lu L, *A top-down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas*, Atmospheric Environment, Vol. 38, pp. 2737-2748, Elsevier Science Ltd., 2004.

Sailor D, Fan H, *The importance of including anthropogenic heating in mesoscale modeling of the urban heat island*, Presented to: 84th Annual AMS conference, Seattle, January, 2004.

Steadman J P, Bruhns H R, Rickaby P A, *An introduction to the national Non-Domestic Building Stock database*, Environment and Planning B: Planning and Design, Vol. 27, pp. 3-10, Pion Publications, Great Britain, 2000.

Steadman J P, Bruhns H R, Holtier S, Gakovic B, A *Classification of built forms*, Environment and Planning B: Planning and Design, Vol. 27, pp. 73-91, Pion Publications, Great Britain, 2000.

Steadman J P, *Carbon Emissions from the Building Stock*, Lecture Given to MSc Environmental Design and Engineering Students, The Bartlett, UCL, 1-19 Torrington Place, London, February 7, 2007.

Taha H, *Urban climates and heat-islands: albedo, evapotranspiration, and anthropogenic heat*, Energy and Buildings, Vol. 25, pp. 99-103, Elsevier Science Ltd., 1997.

Upmanis H, Eliasson I, Linquist S, *The influence of green areas on nocturnal temperatures in a high latitude city (Goteburg, Sweden)*, International Journal of Climatology, Vol. 18, pp. 681-700, 1998.

Yamaguchi Y, Shimoda Y, Mizuno M, *Proposal of a modeling approach considering urban form for evaluation of city level energy management*, Energy and Buildings, Vol. 39. pp. 580-592, Elsevier Science Ltd., 2007.

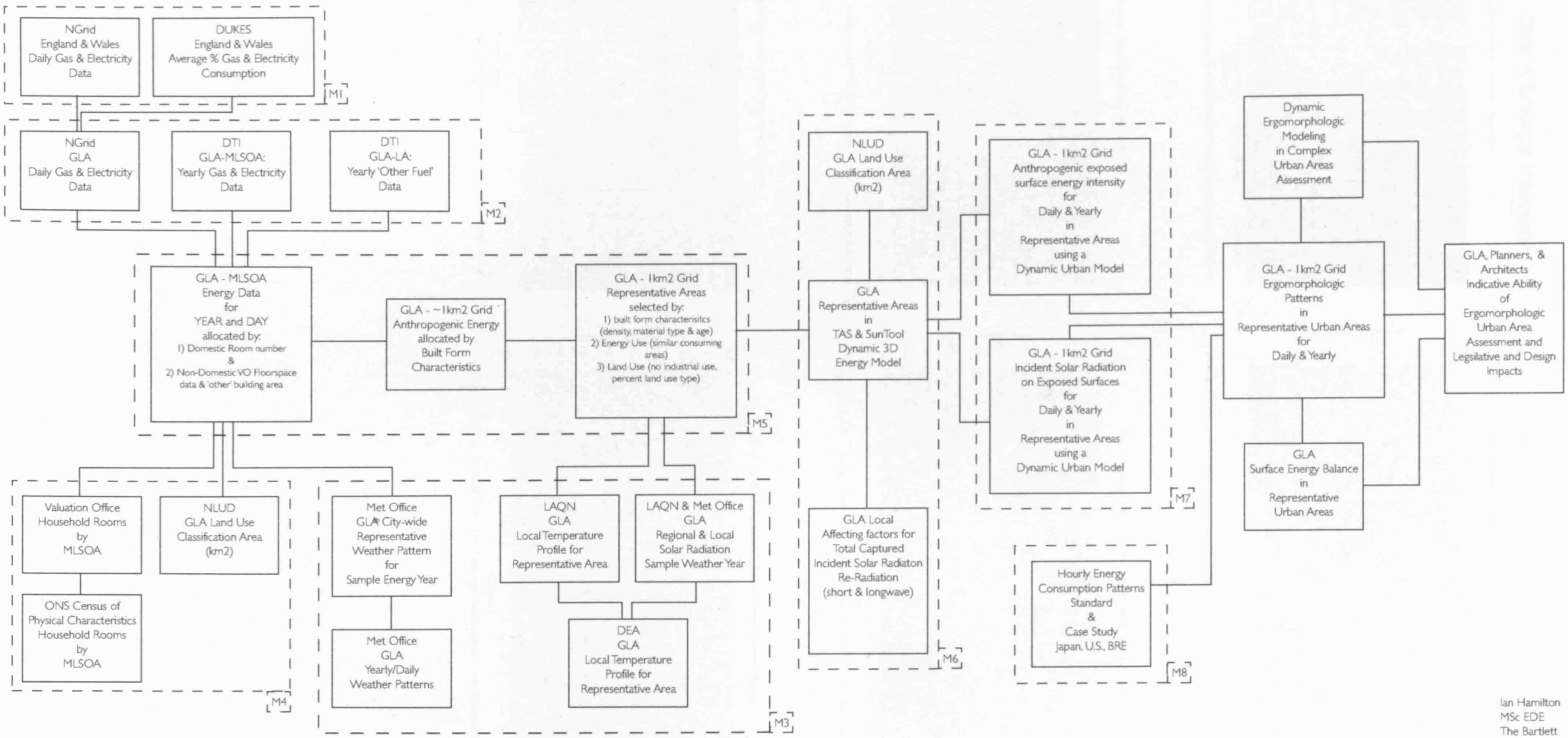
Yao R, Steemers K, *A method of formulating energy load profile for domestic buildings in the UK*, Energy and Buildings, Vol. 37, pp. 663-671, Elsevier B.V., 2005.

Watkins R, Palmer J, Kolokotroni M, Littlefair P, *The London Heat Island: results from summertime monitoring*, Building Service Engineering Research and Technology, Vol. 23, Issue 2, pp. 97-106, The Chartered Institution of Building Services Engineers, 2002.

World Meteorological Organization, *WMO Statement on the Status of the global climate in 2005*, UN – World Meteorological Organization, 2006.

GLA Surface Energy Balance - Flowchart

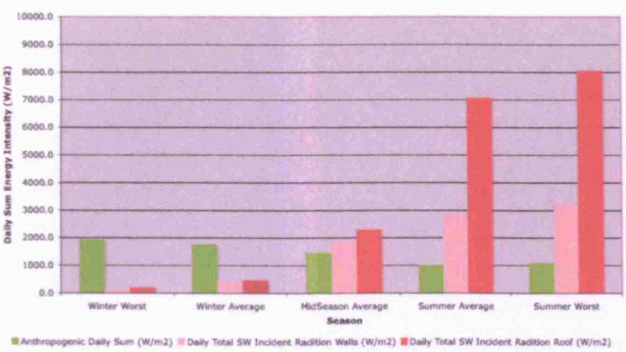
M - Methodology (see Methodology Outline)



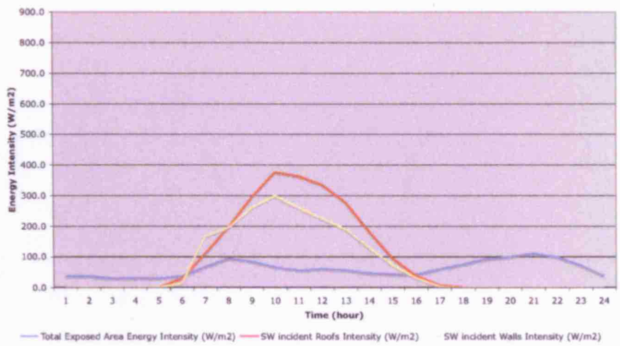
Ian Hamilton
MSc EDE
The Bartlett

Graphs and Charts - Site A Energy Intensity

Site A: Daily Energy Intensity Sum for Seasons



Site A: Average Mid-Season Day - Solar & Anthropogenic Energy



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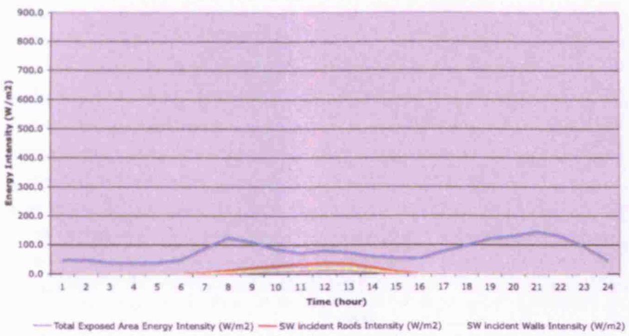

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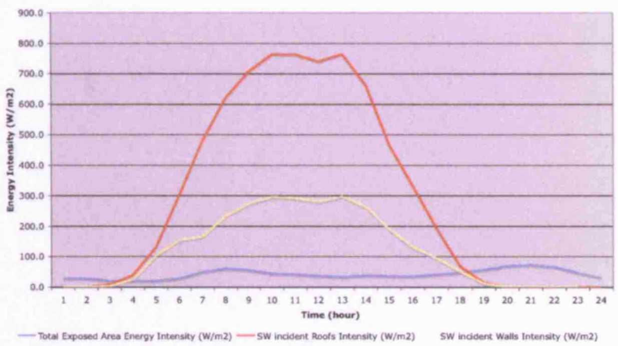

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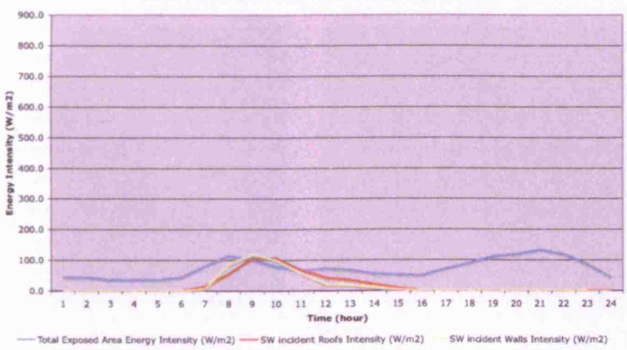

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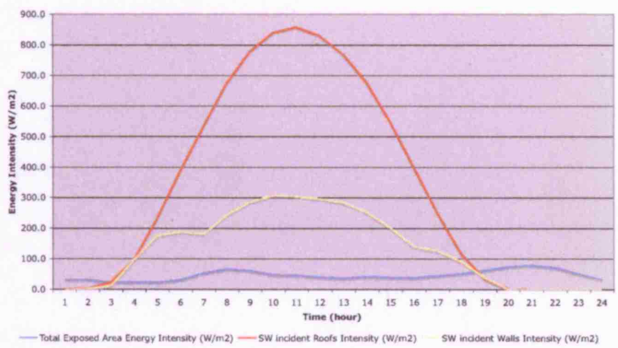
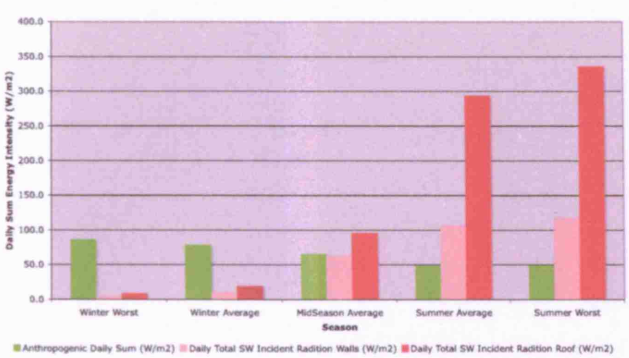
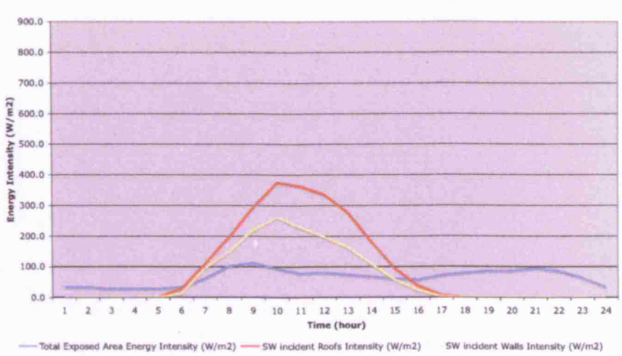


Graphs and Charts - Site B Energy Intensity



Site B: Daily Energy Intensity Sum for Seasons



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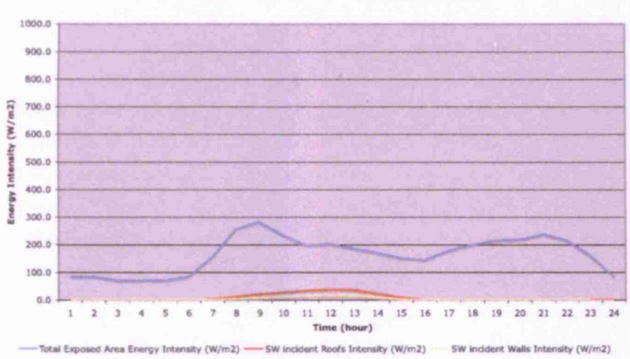

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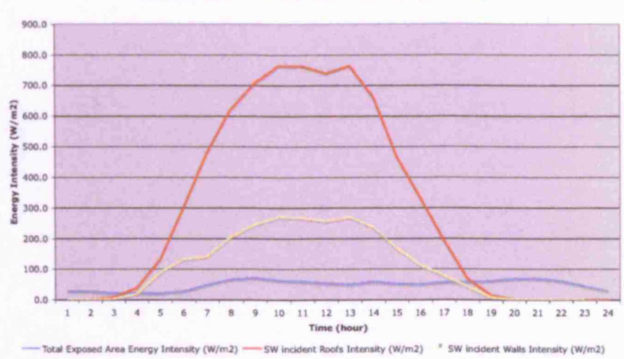

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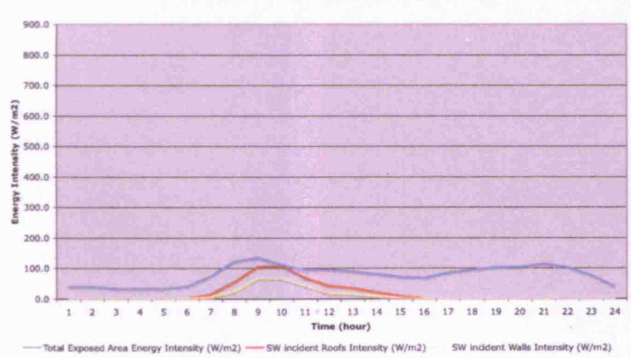

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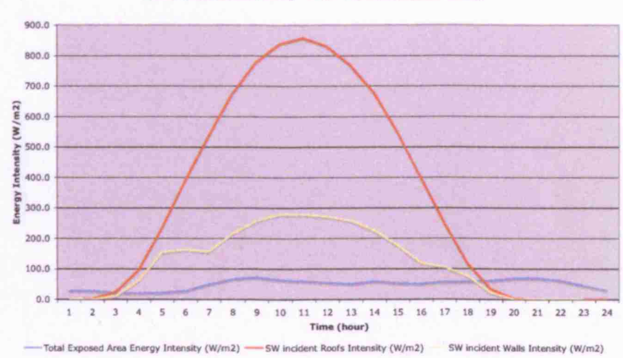
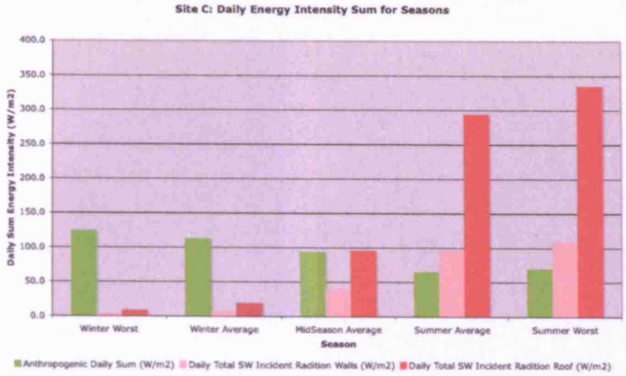
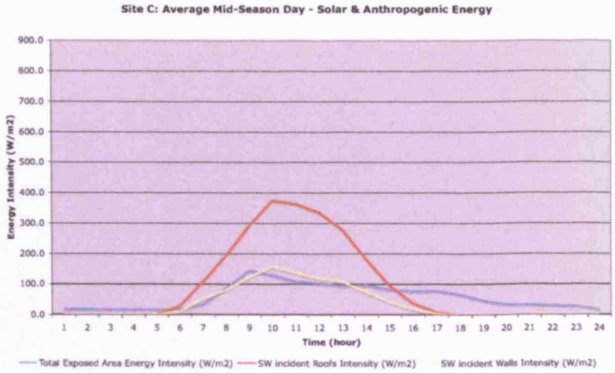
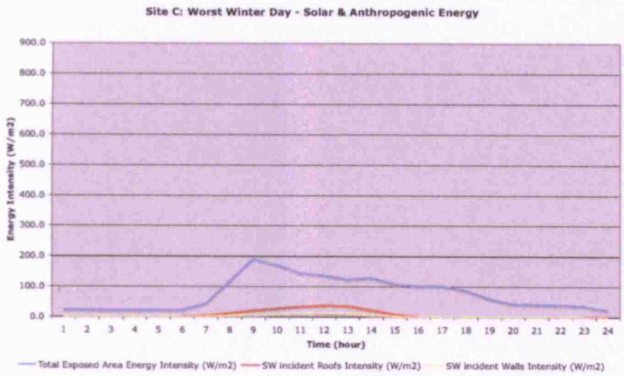


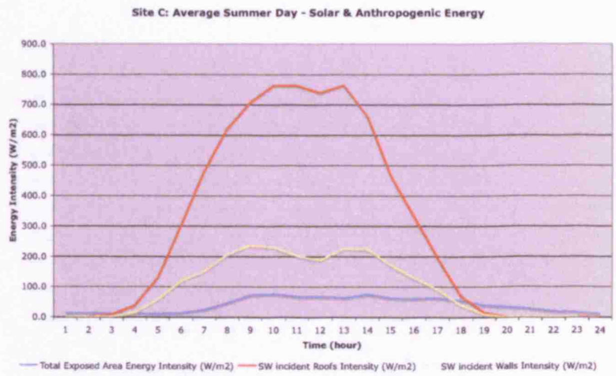
Site B: Worst Summer Day - Solar & Anthropogenic Energy

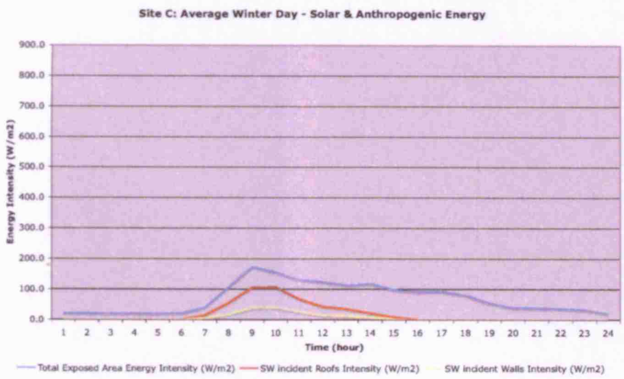
Graphs and Charts - Site C Energy Intensity

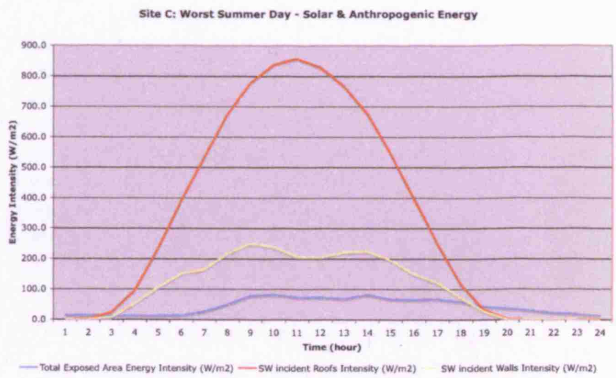






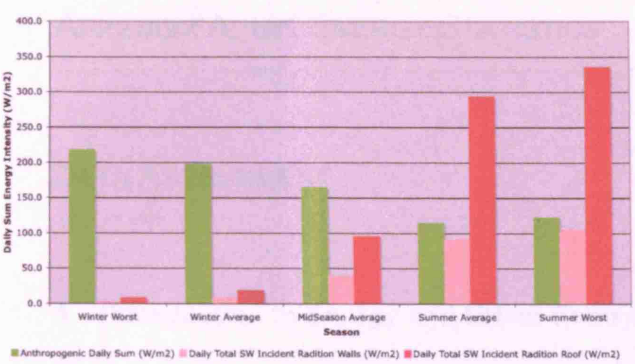




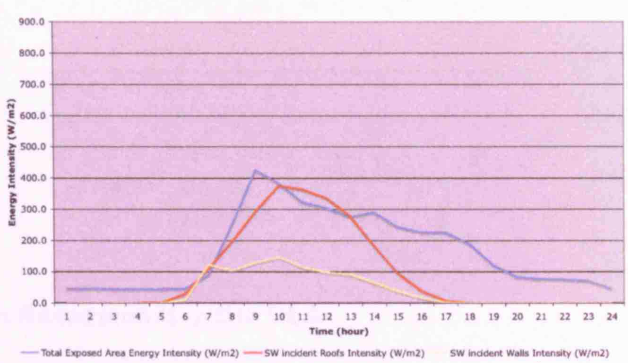


Graphs and Charts - Site D Energy Intensity

Site D: Daily Energy Intensity Sum for Seasons



Site D: Average Mid-Season Solar and Anthropogenic Hourly Energy



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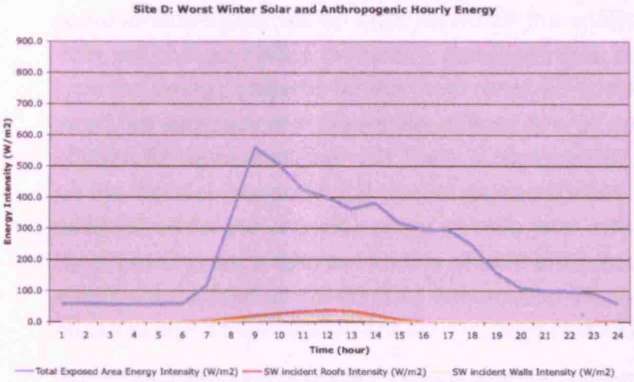

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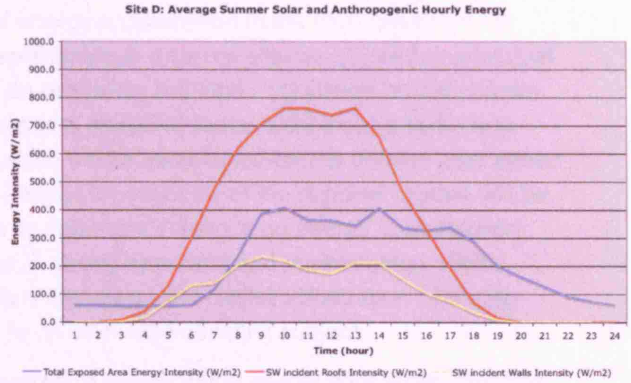
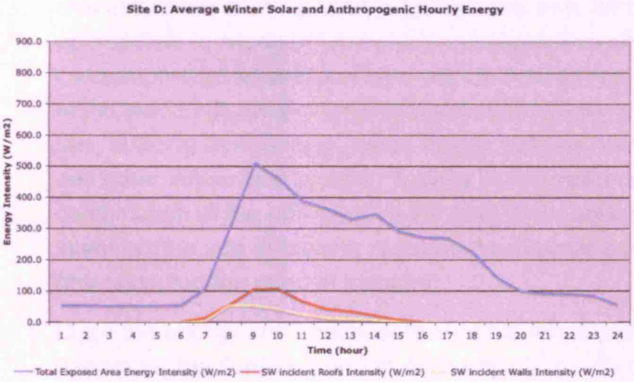
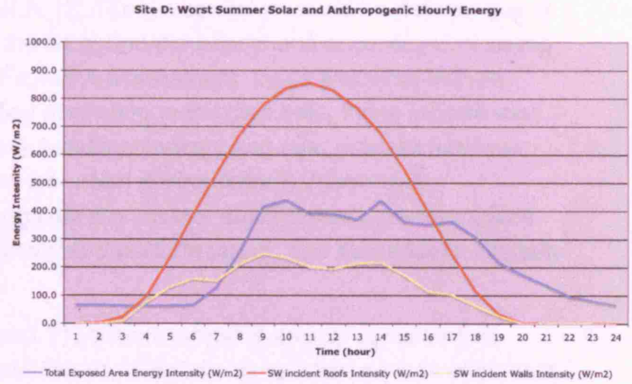


Site D: Average Winter Solar and Anthropogenic Hourly Energy



Site D: Worst Summer Solar and Anthropogenic Hourly Energy



Appendix A: UK Energy Statistics

Data Assessment

1 – Introduction to Energy and Urban Form Data Assessment in the GLA

The following is an examination of the available data sets, their collection methods, inherent idiosyncrasies, inconsistencies, and limitations. (1) All the energy data sets, based on fuel types, will be listed and have the above issues explained. (2) Once the energy data sets have been explained, a representative year will be established for the analysis of energy consumption in the GLA based on the data set characteristics (accuracy, completeness, and representative external effects). (3) Within each fuel type the energy patterns for the most resolved scale will be outline for the GLA. (4) Based on the chosen year, the accuracy and availability of finer energy consumption, temporal scales will be considered and chosen for representation. (5) Then, a representative pattern will be established for the chosen year based on the highest, temporal and spatial characteristics. (6) Finally, an overview of the regional climate will be established for the chosen energy sample year, which is an important influence on energy consumption. By assessing each data set and its related idiosyncrasies, a strong approach and methodology will be established based on reasonable assumption for creating a complete, and realistic illustration of energy consumption at the defined spatial and temporal scales, in an otherwise complex subject.

After the energy consumption data is outlined and rationalized, a review of the spatial data within the GLA will be performed according to the outlined spatial scale, with influencing local urban characteristics identified. (1) As with the energy use, the first step will be to list and identify the limitations and characteristics of the available spatial data sets for the GLA. (2) Then, a spatial level will be defined that is appropriate to represent the energy consumption within the GLA, and the effects and accuracy of showing consumption at a particular level will be considered. (3) From the assessment those elements that are expected to influence energy consumption will be identified according to the data sets, these include land use, building morphology (mean height, volume, surfaces), building typology and age, process intensity, and other influencing factors. Energy consumption within the urban environment is driven by a combination of the efficiency of the built form (ability to regulate the internal environment), the floorspace intensity (the use of fuels to regulate the internal environment and perform tasks), and the process intensity (the consumption used in industry).

Once the energy and spatial data sets have been reviewed, (1) a representative energy consumption pattern for the Greater London Authority (GLA) will be established using energy and fuel consumption data from the national, regional, and local authority level at different temporal scales. (2) To illustrate how the spatial energy consumption changes over the course of the year, estimated yearly, monthly and diurnal patterns will be established using the available data sets and established sector consumption. (3) From the data, a pattern can be established for a middle layer super output area (MLSOA) within the GLA by considering the involved spatial collection points, the estimated floorspace intensity, and the process intensity characteristics within the area. (4) In order to establish a realism that is consistent with such a resolution, the available data sets and sources will be compared for fit and assumptions will be based on known land-use, density, climate, and energy intensity characteristics. What follows is an assessment of the energy data sets.

2 – Data Set Examination

Gross primary and delivered building fuel consumption data at a regional and local authority (LA) level at yearly intervals can be obtained from the Department of Trade and Industry (DTI) for all fuel types (gas, electricity, transport, 'other') and for the total final energy consumption. Specifically, gas datum is available from the National Grid at yearly consumption rates, which are based on the postcode sector for the whole of the United Kingdom (UK). Gas data regarding physical flow into the national transmission system (measured at million cubic meters per day - mcm/day), actual commercial demand by local distribution zones (LDZ) for a 24hour period, and monthly system demand for the LDZ are also available. Electricity data at the middle super output layer is also available from the DTI for yearly periods, but no available data exists at a higher temporal scale. The National Grid also provides some electricity flow data at half-hourly and 15minute instantaneous demands for the whole of the UK transmission network, but the data is aggregated due to the restructured local network ownership scheme [National Grid, 2006]. The Digest of United Kingdom Energy statistics (DUKES) provide national primary consumption data (petroleum, gas, electricity, other fuels) at a yearly output and can be used as a comparative source.

The available energy consumption data sets will be used to provide a temporal and spatial energy consumption pattern for the Greater London Authority resolved to the highest possible spatial and temporal resolution.

3 – Energy Networks

The 'Regional Energy Consumption Statistics' developed by the DTI lists the regional (NUTS1) and local authority (NUTS4) gas, electricity, road transport fuels, and other fuels (manufactured solid fuels, renewables, industrial petroleum and coal). Experimental data at the MLSOA level has been developed for the electricity energy consumption, but no others at this point. The National Grid, operator and owner of the high-voltage electricity transmission network and the majority of the natural gas transportation system, provides gas and electricity data by local distribution zones, and for the whole of the UK at a variety of temporal and spatial scales. EDF (électricité de France) energy networks is the main electricity provider to the southeast of England, they do not provide data of energy consumption from their networks, but their total is quantified within the National Grid UK flow data. Petroleum fuel is delivered

4 – Electricity

4.1 – Context in the UK

The current electricity context for the United Kingdom has shown that since 1970 electricity consumption has grown by approximately 55%, with the growth rate being even between the domestic and industrial sectors, but with a 2.5 fold increase in the administration, transportation and commercial sector [DTI: DUKES, 2007]. Net imports have fallen since an all-time high during the 1990's to approximately 2.2% of the current total UK supplied electricity. Current electricity consumption within the UK is relatively evenly distributed between the industrial (119.51TWh), domestic (116.81TWh) and the other sectors (109.6TWh) [DTI: DUKES, 2007]. Due to the inherent nature of electricity, total aggregate demand flow is a good indicator of consumption, because storage is not possible, unless converted into another fuel type (i.e. pumping storage), which can be roughly accounted for from the consumption statistics.

4.2 – Context in GLA

Electricity consumption in the Greater London Authority is currently approximately 33.8TWh per year [MOL, 2006]. The GLA estimates domestic energy consumption using 2001 census data, which indicates that the electricity demand is approximately 3,300kWh per household. Non-domestic electricity consumption is derived from a 2003 BRE Study that uses floorspace data, with approximately 56.9 million m^2 requiring 154kWh/m^2 or 8.76TWh. Issues that compound the use of electricity in the GLA are the continued growth in population, the decreasing numbers per household, and the continued strengthening of the financial services and their requirements (i.e. operation schedules) [MOL, 2006]. Within the GLA there are 5 electricity plant generators that provide power directly to the city, they are located in Barking, Charterhouse St – City of London, Taylor's Lane - Brent, Enfield, and Landmann Way – Lewisham. These provide a combined peak load of 1.5GW [DTI: DUKES, 2006].

"Approximately 40 per cent of London's 1999 electricity consumption was generated at 17 locations within Greater London. These include 1GW at Barking and 350MW at Enfield, as well as the 180MW plant at Lots Road. The equivalent of about 60 per cent of London's electricity demand is met from power stations outside the capital" [MOL, 2004].

4.3 – Electricity Data

Electricity data is collected through the electricity industry from actual meter readings, meter point reference number's, the distribution companies meter point administration system, and collection agents, where the data is then merged and mapped according to postcodes and aggregated to the LA level. The datum consists of approximately 29 million non half-hourly meters (domestic and small/medium non-domestic) and 85,000 half hourly meters (large non-domestic), where annual consumption is based on annualized advance (AA – estimate between two meter readings) or an estimated annual consumption (uses historic information and the specific meter profile). Users of less than 50,000kWh/yr are considered as domestic users, with users between 50-100,000kWh/yr as high-density domestic (apartment block, or new estates) or small commercial, above this level are considered non-domestic [DTI Guidance, 2006].

The yearly energy consumption data sets released by the DTI are subject to several issues that must be identified in order to qualify the accuracy of the trends with regard to the GLA. (1) Large industrial users linked directly to the high voltage mains are not covered in the data (represent approx. 2% of UK electricity sales); therefore any central volume allocation users (large non-domestic) within the GLA will not be represented. (2) Data quality has changed since 2003, and accuracy in industrial/commercial consumption has improved, where refinements have re-allocated large domestic users who were assumed to be small commercial operations and un-tangible uses (street lighting, un-metered, etc…). (3) Un-allocated levels of consumption have fallen since 2003, with only 1.5% being un-allocated to the local authority level. However, because the data was collected via postcodes there are inaccuracies, which are most evident in the industrial/commercial sector. It is recommended by the DTI, that for comparative purposes, the 2005 data sets, which have the highest level of accuracy, should be used as a baseline.

The DTI, as of 2004, released a middle layer super output area electricity consumption analysis data because of the statistical benefits involved in that level of measurement. The MLSOA level is part of the geographic hierarchy employed by the Office of National Statistics as a method of providing disaggregated data, in this case energy data. The MLSOA have a relatively consistent population (approximately 5,000 or 2,000 households) and is not subject to frequent border re-arrangement [DTI MLSOA Electricity, 2007]. The data set estimates the annual electricity consumption for each MLSOA within each LA in the UK, and distinguishes between three meter types, domestic, Econ7, and commercial. The Domestic and Econ7 meters are domestic electricity consumption and the commercial is all other non-domestic consumption. The domestic sector data was validated via census data and feedback from the LA's. The electricity data was taken from the 2005 DTI 'Energy Trends' publication. The DTI attempts to allocate the electricity use by the three sectors, but the industrial half hourly meter consumption is not allocated to the MLSOA level due to data disclosure issues, and the small number of industrial consumers within the LA. This poses a problem to the realistic spatial allocation of a large portion of the non-domestic data to the middle layer level.

In addition to the DTI yearly consumption data, quarterly and monthly tables are produced for the whole of the United Kingdom. The data provides consumption levels for England and Wales, but does not distinguish between regions or local authorities. The data is current from 2005, but does not provide quarterly information previous to that year. DTI derived these energy trends from the same sources that were used for the yearly consumption statistics. Therefore, using quarterly and monthly totals for England

and Wales, a pattern for the GLA can be postulated by comparing the total annual energy consumption for the GLA and its approximate percentage of the total consumption for England and Wales. From the comparison, quarterly and monthly data can be estimated for the GLA; however, because 2005 is the only available year for such an analysis, the trends may not truly be indicative of actual historic consumption. Though this process has its limitations, it will be possible to provide a higher temporal resolution for electricity consumption within the GLA.

The National Grid provides half-hourly electricity flow data for an annual period for the whole of the UK; the data separates England and Wales to provide energy consumption for 2004 -2006. This data can also be used in the same manner as the DTI monthly data sets, by extracting the expected GLA energy consumption pattern via the percent of the total for England and Wales. In addition to half-hourly demand data, instantaneous 'real-time' data is collected at a 15min scale. It is the sum of all the generation output connected to the transmission system plus imported electricity from France and Ireland. The data consumption does not account for pump storage or station transformer demand, and thus may not reflect wholly accurate energy patterns. However, it could be expected that the sum of the UK delivered data from the total instantaneous flow data would account for these factors. Again, because the data availability is limited to only a collection of recent years (2004-2006) the data must be analysed for irregularities (ie. climate, distribution, process intensity, etc...). By normalizing the finer-scale temporal data to the expected spatial and annual GLA electricity consumption, a pattern will emerge which can be used to represent a dynamic energy consumption map for the GLA.

5 – Gas

5.1 - Context in UK

Natural gas consumption in the UK has increased since the 1970's by 84.2%, with the complete decline of town gas. The majority of the growth in methane (natural gas) consumption has been in the domestic sector and the electricity generation sector, which currently consume 35.2% and 30.7% of the total gas demand respectively [DTI: DUKES, 2007]. The 'dash-for-gas' for electricity generation occurred in the 1990's, subsequently increasing demand for natural gas and production from the North Sea. However, the UK no longer produces sufficient supply to meet the growing demand and has become a net-importer since 2004 [National Grid, 2006]. Due to gas being mainly used for domestic consumption and electricity generation, it is subject to relatively regular consumption patterns; however, due to its distinct nature natural gas consumption is not reflective of actual delivered consumption by the domestic or energy generation sectors (Source, YEAR). Other issues with the demand of natural gas are its increasing cost and limited supply, which have created load responses reflective of the cyclical changes during the year (i.e. Winter months), which in turn affects the consumption patterns.

National Grid, the current owner and operator of the natural gas transportation system, divides the system into local distribution zones, and is responsible for the maintenance and operation of the system. Some portions of the system have been sold and NGrid is not responsible for these and does not collect data for them; these systems account for approximately 90*% of the whole system [National Grid Website, 2007]. In addition to storage and unaccounted gas flow, exports from the system to Ireland, direct subtraction to large industry, and shrinkage, all play an important role in estimating a realistic consumption of gas within the system.

5.2 – GLA Context

Gas consumption within the GLA is used primarily for domestic heating/cooking, industrial processes, electricity generation, and combined heat and power systems. Natural gas consumption in the commercial sector is relatively low in comparison to the above sectors due to its occupancy schedules and internal gains from appliances [MOL & Greenpeace, 2006]. The Mayor of London expects future energy consumption in the GLA to be highly dependant on gas, approximately 60% of the total primary energy, as both the domestic and commercial sectors continue to grow and accommodate the half-million new homes and 16.4million m^2 non-domestic floorspace [MOL & Greenpeace, 2006]. The natural gas system within the GLA receives gas from two local distribution zones, the North Thames and South Eastern, which collectively have 1 storage facility and 6 off-take points [National Grid, 2006]. Off-take points are the locations from which gas is taken from the transmission system. The two zones are large, and due to the above-mentioned intricacies of the natural gas supply and storage system, the link between estimated temporal consumption and actual demand are difficult to interpret.

5.3 – Gas Data

Gas data is collected from the National Grid (NGrid) through their postcode sector gas sales. The DTI then aggregates and re-allocates the data according to the LA level. Where postcode consumption data covered more than a single LA area the data was equally divided between the LA's; the same division occurs when confidentiality requires postcode sectors to be combined. The annual quantities in kWh (AQ) data are weather corrected to the National Grid's 35-year trend, and are an estimate of annual consumption under average weather conditions. (1) The gas data has issues regarding the split between domestic and non-domestic consumption, where users of less than 73,000kWh/yr are considered domestic, and those above, non-domestic. (2) Also, the data does not identify very high consumers, such as power stations, and ignores very small independent gas transporters (mostly associated with new housing estates). Therefore, it is expected that the pre-2004 DTI data only cover 70% of the national gas consumption within the UK. Due to the re-structuring of the gas distribution network, data sets post-2004 were collected by an independent company using the AQ method and corrected to a 17-year weather factor, one that is reflective of the recent temperature changes, which are based on a fiscal year collection start rather than calendar (1 April – 31 March). In order to overcome the limitations of the data for the GLA, for the purposes of this study, the data sets post-2004 will be used due to their increased geographic and consumption allocation accuracy, but due to past data collection methods and idiosyncrasies, the data pre-2004 will not be used for comparative purposes, and therefore an accurate historic time-series cannot be detailed. However, despite the difference between the allocation accuracy, aggregate consumption patterns (inclusive of weather correction) can be identified, and those instead will be used to help establish seasonal and diurnal patterns.

The National Grid 's annual postcode sector data used by the DTI is collected using the above methods. Other measurements at a finer temporal scale can be obtained, but tend to be at a greater spatial scale. A series of gas operational data is measured at a monthly scale, among those are storage and injection allocation, total shrinkage, forecast demand, and demand analysis. The Demand Analysis provides an illustration of the total system demand in kWh for the LDZ; it also includes data on the weather variable deviation, demand forecast deviation, and the day forecast vs. actual demand [National Grid NORM06, 2007]. The actual demand is a measured estimate of the supply points, corrected to the weather variable, which display the aggregated demand of a random sample of differing annual demand quantities for approximately 3900 points within the LDZ [JOGT, 2007]. Actual demand analysis within the LDZ is inclusive of shrinkage and is variable according to the change of users and Local Authority advice for appropriate representation. The demand analysis is a partial collection of actual meter readings and an estimate of historic use and composite weather variation; this method of energy consumption provides a relatively accurate portrayal of actual aggregate demand but may hide spikes (other measurements within the system provide information of demand spikes and influences).

Daily energy reports measure system input/output balance, gas trading, shrinkage, weather correction and scaling factor values, price information, and actual demands within the LDZ's. The Actual Demands measures the actual throughput for a single gas day, measured in mcm (million cubic meters) for the LDZ's. The measurement of this daily demand is done by adding the transmission system's direct loads, the local distribution zone off-takes and shrinkage in a manner similar to the postcode data, but relies on 1600 meter points [National Grid SISR04, 2007].

The National Grid measures gas by its volume (m3, or mcm) passing into each charging zone (i.e. East Midlands, South East, Scotland, etc...) by the gas shippers and suppliers, which is then used in the energy measurement and billing. The gas volume is converted into energy by using the calorific value (CV), which is the measure of heat power released from a known volume and dependent on the composition of the gas (make up of methane, ethane, carbon dioxide, etc...). The CV of the gas passing through the national transmission system varies between 37.5 MJ/m3 and 43.0 MJ/m3, and 93 MJ/m3 if liquefied (received at Stornoway, but then re-gasified) [National Grid - CV, 2007]. The NG use a standard value of 39 MJ/m3 when providing estimates of gas energy, and will thus be used as the standard value in this study.

The GLA consumes approximately 60% of the commercial demand within the two LDZ's and could be used to represent aggregate consumption. However, at a national scale, the GLA consumes approximately 12% of the delivered gas. This figure was ascertained by comparing the regional and UK national consumption statistics [DTI, 2006]. This figure can then be applied to the National Grid's actual demand gas data, which will provide a picture of the energy consumption by the GLA for each day over the sample period. The limitation of this method would be the loss of demand spikes and diurnal data. However, the current measured gas data does not provide this accurate picture due to issues of storage, import/export, shrinkage, and measurement stations. Again, the diurnal delivered energy consumption of natural gas is difficult to show for the GLA as these issues of shrinkage, storage and injection, and measurement points are not resolved to a fine spatial scale. The most appropriate method would be to have temporal data at the meter point level (individual or postcode sector data). Instantaneous flows into the national transmission system are measured from zone supply points, but this data cannot be reliably allocated to a single geographic area due to the interconnected nature of the NTS [National Grid, 2006].

6 – Road Transport Fuel

Road Transport Fuel is an important aspect of the anthropogenic heat flux into the local urban climate; in the GLA this usually equates to approximately 30% of the energy consumption within the urban environment [MOL, 2004]. "In 1999, the London Underground accounted for around one per cent of London's total energy consumption, and three and a half per cent of electricity consumption."

"The system generated about 60 per cent of its needs from the 180MW (megawatts) Lots Road Power Station (closed in 2002). The remaining 40 per cent was obtained via the National Grid, supplied by British Energy, which derives 75 per cent of its power from nuclear power stations, including Dungeness and Sizewell. Peak load on the Underground is estimated to be 200MW (pg. 10).

The road transport fuels are not to be included in this study.

7 – Other Fuels:

7.1 – Context in the UK and GLA

Traditionally, the majority of delivered energy consumption within the UK was coal and other solid fuel forms (coke, bio-fuels). Since the 1970's coal has been virtually replaced by methane gas, and is being eliminated in all sectors, as the price and availability of gas was stabilized. Aside from solid fuels, industrial petroleum is still used across the country; however, demand for this particular fuel source has declined along with the de-industrialization of UK industry and the rise of the service sector [DTI: DUKES, 2007]. In addition to the traditional fuel types, renewable energy is increasing, with the approval of many new wind and biofuel schemes resulting in a 4 fold increase in renewable energy since 1990 [DTI: DUKES – 7.1, 2006.

Though the net of 'other fuels' is cast over a large selection of resources, the overall contribution to the consumption of delivered energy in the UK was approximately 1% in 2001, and is currently 2.5% of the total final consumption [DTI: DUKES, 2007].

7.2 – Other Fuels Data

The other fuels (manufactured solid fuels, renewables, industrial petroleum and coal) consumption data is an estimate of the energy used at the LA level, collected via combination point and area source data. The data is collected by a contractor (AEA Energy and Environment), which use a variety of methods (undisclosed). The data is not actual and is estimated using models rather than surveyed, with the estimates largely derived from the Environmental Agency pollution inventory of air pollutant (CO_2, NOX, SOX) estimates from 1km2 blocks household survey data, population census data, high spatial industrial and commercial employment data, and industry pollution levels, amongst other minor sources. The data does not account for local renewables consumption. Accuracy for such highly modeled estimates is based on the detailed spatial resolution and the resulting influence on energy consumption and the collaboration of sample collecting. The accuracy of the data is limited by its heavy use of modeling, especially for small non-domestic and domestic users, but later data sets (2004 and beyond) will be based on finer spatial information, thereby increasing accuracy.

The percentage of other fuels, when compared to the gas and electricity data, within the GLA is relatively small, approximately 3.34% of the combined gas and electricity consumed in 2004, and 2.74% of 2003 [DTI, 2005]. In 2004, the percent of the total energy consumption was 2.42%, most of which was generated by petroleum product use in industrial and commercial applications. Though this does not make the other fuels components insignificant, it simply indicates that variations of the total consumption due to data set inaccuracies will be marginal. In general, the use of this data must be considered as illustrative rather than indicative of the actual energy consumption of other fuels within the GLA, and due to its relatively low percentage of the total energy consumption, this would seem acceptable for the scope and intended resolution of this study.

8 – The Data Sets

The analysis of the above energy consumption data sets from the DTI indicate several things that must be remembered during the analysis of GLA energy consumption. These are: (1) that energy consumption data is largely estimated, mostly from actual meter readings (using the AQ method), and thus, highly resolved accurate historic temporal patterns (i.e. diurnal) will be very difficult to assess; (2) that energy consumption data's spatial resolution at the MLSOA is subject to in-accuracies resulting from privacy and unknown land-use data; (3) that allocating energy consumption to the MSLOA is either derived from re-aggregated postcode and postcode sector data (gas and electricity) or divided down from the local authority level based on land-use; (4) that gas and electricity amount to the majority of current energy consumption (upwards of 74%) within the GLA; (5) that both gas and electricity data contain high-usage user and independent distributor gaps, with some completely unaccounted for; and (6) that due to restructuring and refined collection techniques, later data years are more accurate for high resolution studies, as more energy is accurately allocated to the MLSOA level.

Despite these limitations, for the purposes of this study, the above DTI data is of reasonable spatial accuracy for a MLSOA resolution. By using the more recent DTI 2004 data as the representation of the energy consumption for the GLA, in addition to having accurate spatial allocation, the climatic conditions of that particular year should be considered for its representative features as climate and energy consumption are closely related.

9 – GLA Energy Synopsis – 2004

Having characterized the available energy data sets and chosen the most representative year, an outline of the actual energy used within the GLA for the 2004 year will be useful for further resolving the consumption to the Middle Layer Super Output Area. The MLSOA is the most appropriate urban scale for an energy assessment as the available collected accuracy of the actual energy use is highest and the building characteristics are most easily aggregated according to typology and morphology.

The current total energy consumption for the GLA in 2004 was 169.7tWh, with 59.91tWh, 67.2tWh, and 42.5tWh's assigned to the non-domestic, domestic, and transport respectively. The energy used in transport within the GLA is mainly from petroleum fuels; however, Transport for London does use a considerable amount of electricity for use in the Tube system. As indicated above, the main sources of energy within the built environment of the GLA are gas and electricity. Gas consumption, provided only at a Local Authority level output, for the whole GLA was approximately 82.7tWh, or 48.73% of the total energy. The average consumption within the domestic sector is 1.6tWh with a standard deviation 0.53tWh and 31.5% of the total energy. The average consumption within the non-domestic sector was 29.2tWh, with a standard deviation of 0.55tWh or 17.24% of the total energy. Electricity consumption, provided at the MLSOA level, for the whole GLA was 40.3tWh, or 23.78% of the total energy. The non-domestic electricity consumption is twice that of the domestic use (26.8tWh and 13.5tWh respectively), likely a product of commercial floorspace intensity and process intensity. The other fuels (coal, manufactured fuels, petroleum, renewable and waste) account for a very small percent of the total energy consumption, a combined 2.42%. Within the built environment, gas and electricity account for 96.7% of energy consumption within the GLA, with the other fuels providing the rest (petroleum fuel the largest portion).

In order to create an accurate representation of the energy use at the MLSOA level, the gas and other fuels, collected only at the LA level, must be further resolved. This process will investigate which built form spatial characteristics are the best indicators of local energy consumption, and will then provide a realistic illustration of the 2004 energy consumption. This pattern will then be used for the comparison between the built form characteristics and the experienced solar radiation.

10 – Established fine-scale temporal patterns

Energy consumption patterns data and statistics have been largely established for year-periods but have not been readily established for a finer temporal scale (i.e. monthly, daily, or hourly), due to the variable nature of such an estimate. This presents a problem in being able to produce 'accurate' historic energy consumption, and thus anthropogenic heat input patterns for the GLA; results will be influenced by assumptions regarding demand and variation.

Rather than produce an illustration of daily consumption based on national consumption patterns, the more appropriate seasonal scale will be established using seasonal energy consumption patterns.

It is necessary, therefore, to make best approximations of key data sets where only yearly or per-capita data is available; this sort of approximation can be made by comparing yearly consumption with per-capita consumption multiplied by established seasonal patterns. Again, not as accurate as collected data, but a pattern can be inferred and used to comment for a specific time and year.

As London is the dominant influence over, and indicator of, energy consumption in the southeast of England, patterns within regional data sets will be largely representative of the GLA's consumption patterns. For this reason a normalized representative yearly, monthly, and daily pattern can be established for per-capita energy consumption for London. This level of resolution would be acceptable for a projection, but could only give a representation of 'real-time' data and would be subject to the unique set of limitations for individual or fine-resolution areas (super-output areas) within the city.

Relationships between fuel types and expected temporal and spatial patterns can be profiled for energy consumption data sets for London, based on average 'regional' or local per-capita patterns. Gas and Electricity energy consumption will follow relatively consistent seasonal flow patterns [National Grid - Actual Demand, 2007] and can be used to indicate how energy consumption patterns will change per-capita (person, land-use, floor-area) over time for a given spatial resolution. By 'profiling' the energy consumption patterns a normalized view can be established per-capita or by land-use type and can be applied to areas around the city. This same approach will be used to establish a total energy-use profile for the year, seasons, and perhaps at an hourly scale.

Spatially, if an NUTS4 energy consumption is known, and land-use, floor area and density can be established at a finer scale (SOA), then an energy-use profile can be used to create expected energy flow. This profiling can be applied to both a meso and micro city area scale. Obviously, the finer the scale, the more spatial parameters should be included in order to have a higher degree of accuracy.

11 – Representative Energy Consumption

The above analysis of the energy consumption data sets indicated that the post-2004 data would be most representative of the GLA's spatial and temporal energy consumption, as it is able to most accurately allocate consumption trends, and also that the weather year can be classified as average of the current climate conditions.

Sources:

BRE, *The UK Potential for Community Heating with CHP*, Building Research Establishment, November 2003.

Boutet T S, *Controlling Air Movement: A Manual for Architects and Builders*, London, McGraw-Hill, 1987

DTI, Total Final Energy Consumption at Regional and Local Authority Level: 2004, Department of Trade and Industry, Webpage: http://www.dti.gov.uk/energy/statistics/regional/total-final/page36187.html, Accessed: May, 2007

DTI, *DTI Middle Layer Super Output Area Electricity Consumption Analysis*, Department of Trade and Industry, December, 2006.

DTI - Guidance, *Guidance note to assist local Authorities to Interpret The DTI sub national energy consumption statistics*, Department of Trade and Industry, December, 2006.

DTI, *Digest for United Kingdom Energy Statistics 2006*, Department of Trade and Industry, Stationary Office, Norwich, United Kingdom, 2007.

DTI, *Energy Trends: 2006*, Department of Trade and Industry, Stationary Office, Norwich, United Kingdom, December 2006b.

JOGT, *Uniform Network Code – Transportation Principal Document Section H, Version 2.36*, Joint Office of Gas Transporters, Accessed May 30th 2007 Webpage: http://www.gasgovernance.com/Code/UniformNetworkCode/, April, 2007.

LAQN, *Data Downloads: Wind Speed*, London Air Quality Network, King's College London,

Lockwood, J G, *Some comments on long–term trends observed in an east England relative humidity dataset*. Weather, 55, 170–174, 2000

LCCP, *London's Warming: The Impacts of Climate Change – A Technical Report*, London Climate Change Partnership, Greater London Authority, London, 2002.

Mayes J, *South-east England*. In: Wheeler, D. and Mayes, J. (Eds.) Regional climates of the British Isles, London: Routledge, 1997

Met Office, *Services for the Energy Industry*, Met Office, Crown Copyright, Web Page: http://www.metoffice.gov.uk/energy/index.html, Accessed: June, 2007.

MOL, *The Mayor of London's Submission to the Energy Review*, Mayor of London, Greater London Authority, City Hall, The Queen's Walk, London, April, 2006.

MOL, *Green light to Clean Power: The Mayor's Energy Strategy*, Mayor of London, Greater London Authority, City Hall, The Queen's Walk, London, February, 2004.

MOL & Greenpeace, *Powering London into the 21st Century*, Greater London Authority, City Hall, The Queen's Walk, London, March, 2006.

National Grid, *Gas Transportation Ten-Year Statement 2006*, National Grid, 2006

National Grid, *Gas Demand Forecasting Methodology*, webpage: http://www.nationalgrid.com/ Accessed: November 2006b

National Grid, *NORM06 – Demand Analysis*, webpage: http://www.nationalgrid.com/ Accessed: April 2007.

National Grid, *SISR04 – Actual Demands*, Energy Daily Reports, Operational Data, webpage: http://www.nationalgrid.com/ Accessed: April 2007.

National Grid, *Actual Demand 1998-2007*, webpage: http://www.nationalgrid.com/ Accessed: April 2007.

Oke T R, *Boundary Layer Climates, 2nd Edition*, Routledge, London, 1987.

APPENDIX B: GLA ENERGY CONSUMPTION ASSESSMENT

1 – Introduction

The energy data and land use characteristics provide an overview of the available information that will be used to map the GLA's energy consumption at the most representative spatial and temporal scales for the study of energy consumption and built form and the expected resulting effect on the urban climate. The review of the 2004 London climate data helps establish the representative nature of using the energy consumption data within the GLA.

An annual energy consumption pattern at the MLSOA scale will provide an example of realistic energy use within the GLA. It is an aggregated example of a particular year (2004), but can be considered representative of the current energy consumption patterns across the city as influenced by the climate and local characteristics (aggregate land use, sector clustering, built-form density, and floorspace and process intensity).

2. – Annual Energy Consumption Methodology

2.1 – GLA Energy Consumption Model

The method of calculating the energy consumption within the GLA is done using a simple spreadsheet model (GLA Energy Consumption Model) that links the appropriate energy databases of the desired year to the specific attributes of the local authority and MLSOA. The output of the model is the annual total energy consumption, measured in GWh, for the identified local authority and the MLSOA's within. With this data a multitude of assessments and modifications can be made.

The model's use of spatial attributes is limited to those that are publicly available at the desired LA and MLSOA scale. The process of identifying those attributes that best matched energy consumption is outlined. This method will use data sets similar to other GLA energy consumption studies [GLA, 2002]. The yearly energy consumption can then be cross-referenced to a digital geographic information system map using an NUTS established MLSOA identifier code. The map then provides a citywide representation of the energy used, based on the different fuels used, the built form characteristics, and the particular assumption made for allocating data to the MLSOA level.

2.2 – Model Methodology

The following is the methodology for allocating energy consumption to the MLSOA level:

The model uses the DTI energy data sets due to relative accuracy and the geographic boundary divisions (Local Authority and MLSOA vs. Postcode Sector), the reliability and collection methodology, and the available range (Gas, Electricity, and Other fuels). The local authority level data includes: petroleum, manufactured fuels, coal, renewables, and unallocated electricity. The middle layer data is provided for a portion of the meter types for electricity and gas. The DTI electrical and gas energy consumption is already mostly allocated to an MSLOA level, and can be directly used in the addition of the total energy; however, a portion of the data cannot be allocated to the MLSOA due to the previously mentioned data disclosure guidelines. The electricity domestic data is divided into two meter types, domestic and econ7, both of which have a high allocation rate. The electricity commercial data is allocated to those users not on an industrial half-hourly tariff; it also has a high allocation rate within the MLSOA's. The gas domestic data is relatively well allocated, but there are still a considerable number of large non-domestic users that are not allocated beyond the LA level. The un-allocated data within the LA is a combination of the 'Industrial Half Hourly' data and the Total Unallocated Domestic and non-Domestic electricity and gas use. The data is then distributed based on spatial data within each MLSOA. The LA level data is subdivided by domestic and non-domestic sector data and added to the MLSOA electricity data. The total domestic and non-domestic energy consumption is derived and summed for the total energy consumption by MLSOA.

An initial attempt at using land use built area as an allocating agent by domestic and non-domestic fuel use proved to be too imprecise for the aims of this study. The main limitations were the manner in which the division and allocation of energy gave no impression of process intensity (specifically for industrial non-domestic use), clustering of commercial and industry, and built form density, thus making it difficult to realistically allocate energy consumption for further comparison.

The land use data was corrected to square meters (from thousand square meters), where the percentage of domestic and non-domestic building area are given from the whole of the local authority for use in allocating LA level energy consumption statistics. As an estimate, the total building area provided an indication of the 2-D density within the MLSOA. This form of density cannot be considered a realistic estimation of energy consumption, particularly in the non-domestic sector, where the floorspace and process intensity vary tremendously between individual users and therefore cannot be aggregated easily. The same issues arise in the domestic sector, but less so, as the energy use per individual is more comparable. This is because of the differences in process intensity between the non-domestic sub sectors, where restaurants, plants, and warehouses will all use a considerably different amount of energy [Mortimer et al. 2000].

A second method was devised using the same energy data sets, but different built form characteristics. First, the allocation of the non-domestic energy was performed using the Valuation Office's (VO) 2005 Commercial and Industrial Floorspace and Rateable Value Statistics data at an MLSOA scale, which was collected from the Office of National Statistics' Neighbourhood Statistics. The 5 bulk classes (Retail, Office, Factories, Warehouses, and Other) were totaled for each MLSOA, providing a count of rateable premises and floorspace area. The total floorspace area was then used to subdivide the non-domestic energy data that was only available at the Local Authority Level (Gas and Other Fuels). Summing the MLSOA proportioned LA energy data with the MLSOA gas and electricity data then produced total non-domestic energy consumption for each MLSOA.

The intensity of use provided by this portion of the allocation model is therefore based on the total bulk class floorspace area within each MLSOA. To verify the validity of using VO floorspace data as an indicator of energy consumption, a comparison between the LA floorspace area and LA energy data was performed; the result of which indicated that it would be reasonable to assume energy use was positively linked to floorspace area. A strong correlation coefficient of 0.932, with an r^2-value of 0.8649 was found, which indicated a strong positive. In addition, as of 1999, industrial energy consumption in the GLA was only approximately 7% of the total energy use (includes transport) [MOL, 2004]; this would, therefore, indicate that the allocation method ought to provide a reasonable picture of energy consumption by non-domestic floorspace area.

However, keeping in mind the earlier mentioned limitations of the measurement methods (GIA vs. NIA), the non-domestic data will not cover those areas outside the bulk category measurements (i.e. Schools, Hospitals, etc...). Perhaps a more realistic method would involve using a more complete listing of non-domestic properties based on street address from which to approximate the associated energy consumption based on energy consumption by user type [Bruhn, Steadman, Marjanovic, 2006].

The next step in the model is the allocation of the domestic energy, which involves using household data, rather than built area. The Household Number of Rooms were totaled by MLSOA and used as a dividing method for the domestic energy consumption. The total LA domestic energy was divided by the total number of rooms in each MLSOA, which was then added to the non-domestic energy data.

Using household numbers as an indication of energy consumption within the GLA shows a statistically strong relationship. A correlation coefficient test indicated that there was a strong positive correlation of 0.920 and an r^2-value of 0.8073, and when ranked higher according to number of rooms (correlation value of 0.983). Despite the results, a finer resolution that uses a more appropriate method might be a attained using a combination of both building volume data and number of rooms by accommodation type, as both size and type (thus location and density within the MSLOA built form).

The summed domestic and non-domestic spatial data is then multiplied by the total energy data sets, which are summed again to create the total built form energy consumption per year by middle layer super output area (GWh/yr). The data is then joined to the required GIS data code for use in a GIS mapping program that provides a city-wide diagram of the energy consumption of all the MLSOA's in the GLA for 2004.

This data has a relatively high degree of accuracy as both the domestic and non-domestic data is well related to respective energy consumption at the local authority level. However, 'Industrial' consumption would not be distributed in this manner throughout the Local Authority, but would likely be grouped or centralized in several industrial areas within specific MLSOA's. Also, the non-bulk classes are completely ignored, and may, in fact, prove to have a bigger impact on energy consumption. Due to this inaccuracy, further investigation into specific process intensity is needed in order to accurately allocate this energy consumption to the proper MLSOA.

2.3 – GLA MLSOA Energy Consumption

The linked energy consumption and boundary data provides a citywide pattern of the energy consumption for the GLA's MLSOA. The illustration is characterized by high energy consumption levels within the highly built-up areas within the GLA and the outlying industrial centers. The dense city core is characterized by higher energy consumption patterns, upwards of 1,400GWh/yr in areas of Westminster and well over 3,000GWh/yr in the City of London. Other notable areas are Canary Wharf in Tower Hamlet and Heathrow airport in Hillingdon. This is not an overly surprising initial outcome, as these areas are the governmental, commercial, financial, and transportation hubs of the GLA. Missing is a clear manufacturing hub, which indicates the decline in industry within the GLA, or the inaccuracy due to the limitation of accounting for process intensity; likely it is a combination of the two.

Sources:

Bruhns H, Steadman J P, Marjanovic L, A preliminary model of non-domestic energy use for England and Wales, Proceedings of the Annual Research Conference of the Royal Institution of Chartered Surveyors, RICS, The Bartlett School, UCL, 2006.

MOL, *Green light to Clean Power: The Mayor's Energy Strategy*, Mayor of London, Greater London Authority, City Hall, The Queen's Walk, London, February, 2004.

Mortimer N D, Elsayed M A, Grant J F, *Patterns of energy use in nondomestic buildings*, Environment and Planning B: Planning and Design, Vol. 27, pp. 709-720, Pion Publications, Great Britain, 2000.

APPENDIX C: SITE CHARACTERISTICS AND IDIOSYNCRASIES

To ensure that the chosen representative sites are indeed illustrative of typical 1km^2 MLSOA's within the GLA a further identification of the site characteristics and idiosyncrasies is performed.

The urban morphology, based on the builtspace ratio, volumetric density, urban canyon height and width, allows a relatively complete depiction of the urban form, however, certain elements must be identified before their representative nature can be validated. First, using the builtspace ratio does provide the area that is built upon by buildings; it does not consider other energy consuming devices, like streetlights or bus shelters. The GLUD does provide information on the area of roads, rail, paths, and green spaces, but these are not included in the analysis as they do not directly consume anthropogenic energy, however, they will definitely have an influence on the total incident solar radiation, both within the urban environment (via absorption, openspace increasing solar gains, etc...) and on the exposed energy surface balance (via reflection).

The volumetric density value is derived from the builtspace ratio, and its validity is subject to the area for which it is evaluating, obviously more accurate for smaller spaces. Also, this value is really evaluating the urban space as though it were one large block within an area, this is useful for comparison against other areas, but does not truly represent the varying form, orientation or street layout. It also reduces the amount of exposed area within the urban environment that is likely to be incident to solar energy. Having reduced exposed area will also skew the comparison between the solar and anthropogenic energy, where it is likely to reduce the solar energy and increase the anthropogenic energy. For these reasons, the volumetric density is not used in the actual modeling of the urban environment, but solely for the purposes of establishing and analyzing urban forms. This issue is further resolved in the dynamic modeling methodology.

As indicated from past research, the typology of the built form is difficult to relate to actual building energy consumption, however, at a more aggregated urban scale certain patterns do emerge. Energy use by sector within the built form will not indicate typology, nor will typology likely indicate energy consumption, however, a preliminary assessment of land use and energy consumption by sector does indicate a relationship between areas with high domestic land use and lower consumption. The fact that finer detailed energy consumption values are not available, makes further analysis between land use and energy difficult, however, as several studies have indicated [see Mortimer et al, 2002; Steadman & Bruhns, 2000; Sailor, 2004], this is an area for further research.

In addition, it is likely that urban environments will not have building heights that create a parallel planar canyon, that urban canyon ratios, heights and walls, will vary through the street(s). However, this aspect of the urban canyon form is more important for dense forms, which may be subject to greater amounts of solar energy at the top of the building and very little at the bottom, due to overshadowing.

APPENDIX D: CLIMATE ASSESSMENT

1 Climate

The UK is part of what is defined as the composite zone, an area that is marked by warm/hot summers with low RH and low precipitation and cool moist winters (Boutet, 1987). London's regional climate is a cross between coastal and continental climate conditions, as its sheltered location in the Thames Valley allows for warmer, drier and sunnier conditions than the rest of Britain. Average rainfall in the Thames estuary is 500mm/yr, where the Thames Valley is approximately 600-650mm/yr; this is low in comparison to the averages found elsewhere around the UK [Mayes, 1997]. There has been a decrease in summer rainfall since the 1880's and an increase in winter rainfall over the past 150 years [LCCP, 2002].

London's average temperatures since 1861 to 1999 have shown a rise in temperature of approximately +0.6C, with the warmest occurring between 1989 and 1999 (London Warming Technical Report, 2002). From 1999 to 2004 the average temperature range has been 23-29C with a record-breaking year in 2006 with a maximum temperature of above almost 40°C in central London (London Air Quality Report).

The relative humidity across the region has declined since the 1920's; with the lowest RH's observed during periods of drought. The expectation is that this is to become more frequent in the Southeast. Along with this trend is an increase in potential evaporation throughout the year, but markedly during the spring and autumn months [Lockwood, 2000].

2 Climatic Data Sets, Measurements

The regional climate that surrounds London has a considerable effect on the energy consumption patterns seen within both the domestic and non-domestic sectors [MET Office, 2007]. The National Grid includes a composite weather variable (a measurement of actual temperature, wind-speed, and effective temperature) in their natural gas demand estimates, which is used to include seasonal normals and expected surges in demand [National Grid, 2006]. The degree day is also a commonly used unit for measuring expected energy consumption, particularly in building comfort models, and derives its pattern by counting the number of days within a given time that are above or below a specified value. The composite weather variable is measured in a similar manner.

In order to understand what effect that the weather had on the sample 2004 energy measurement of the GLA, a brief analysis of the local mean conditions will be presented and the source of the data, an overview of the effect the conditions have on the weather estimates, and the variation in demands of particular fuel types (i.e. gas for heating, electricity for air conditioning). In addition to the overall weather influences (temperature, wind, rainfall), the solar conditions (radiation levels, cloud cover) for the 2004 year will be analysed for any particular conditions that should be considered in the modeling of the solar radiation effect within the built environment. Details about the particular issues that affect solar radiation will be outlined and the likely issues that would effect this radiation observed at the building scale.

3 Climate and Energy

National and Regional data is available from the MET office, which includes locally measured temperature, sunshine, pressure, wind speeds and rainfall, in the London area. Their monitoring stations within London (approximately 10) measure a variety of the above conditions, but the main station data sets come from Heathrow Airport (since 2004) and Greenwich (pre-2004). These weather variables will affect energy consumption and electricity generation, particularly for the renewables.

Local scale measurements of pressure, rainfall, solar radiation, temperature, and wind direction and speed, in addition to air pollutant data, are available from the London Air Quality Network. There are over 150 stations around the GLA, covering a variety of urban locations (urban background, rural, roadside, industrial, curbside, etc...). This local scale data will be far more representative of the observed conditions felt within the urban environment of the GLA and will act as a comparative source against the regional Met Office data. An analysis of several sites around the GLA indicated that the urban stations (Shaftesbury, Kensington & Chelsea town center) tended to have higher average peak temperatures than those located in rural or open sites (Heathrow, Greenwhich) by approximately 1-5K. Shaftesbury had an average increased temperature of 5K for the whole of the year compared to the Heathrow station, an obvious effect of the station location and the influence of the built form and anthropogenic heat on the local urban climate.

Historic temperature (1952-2005) data indicates a slight rise in the mean temperature for the sampled year of 2004, the observed mean monthly temperatures are well within the historic average. The observed annual average for 2004 was 11.9°C, and the five and ten-year average were 11.86°C and 12.11°C respectively. The monthly maximum and minimum for 2004 was 15.5°C and 8.2°C, which were within the ten-year average of 15.8°C and 8.3°C. A peak temperature of 23.8°C was observed in August compared to a peak temperature of 26.9°C in 2003. This indicates that the year temperature was very close to historic patterns and could be taken as representative. Since temperature is very important in the estimation of fuel consumption, the National Grid uses weighted temperature values for gas consumption estimates; identifying the normal pattern of 2004 is important for this project's annual energy analysis and the expected seasonal consumption.

Establishing mean wind speed data is far more complicated, given the urban street pattern causing variances due to roughness; however, observed measurements at the Heathrow airport (a more smooth terrain) provide an average wind speed of 3.6m/s and a max speed of 11m/s [LAQN, 2007]. Wind speeds will add to the experienced chill of the air, increasing the convective transfer of heat by removing the static boundary layer from around an object [Oke, 1987]. This, in effect, then influences the temperature and heat loss from and around a building, thus increasing the need for fuel and energy consumption.

4 Influencing Factors on Energy Consumption

Seasonal energy consumption patterns differ for each fuel type according to the end-use and sector. It can safely be assumed that using the 2004 sample year for energy consumption within the GLA will not produce any erroneous patterns due to regional or peak climatic variation as the weather year was relatively normal by temperature and wind pattern standards. Micro scale climate and energy consumption are a product of the regional, local and meso urban climate, the local building morphology and typology, and the floorspace and process intensity.

UK domestic energy consumption follows relatively closely seasonal temperature patterns, with variations attributed to climate or market forces. The impact of temperature on the service and commercial sector is slightly less variable, with only a small seasonal demand pattern. One reason for an increase in consumption during cold months is for space heating, depending on the use and gains from floorspace intensity (i.e. office equipment, kitchens, etc...), a similar reason for the lack of a summer reduction in energy consumption could be attributed to the use of air conditioning and regular floorspace intensity. However, temperature and climate has little effect on the consumption of energy for process intensity, however, the effect that climate might have on process intensity may be on the efficiency of the engine (co-efficient of performance) or device for process itself. Given that any such variation would not be known at an aggregate scale this effect could only be shown by investigating the energy consumption of the industrial meter types by deducting floorspace intensity from industrial intensity. An overview of domestic gas patterns indicate that consumption is strongly influenced by seasonal climate patterns indicate that the main use of the fuel is for space and water heating* [DTI, 2006b]. Non-domestic gas consumption is not so easily linked to the seasonal climate, for the above mentioned reasons of process intensity and end-user characteristics. Total gas demand is positively correlated with degree-days, with higher consumption by meter increasing as the temperature decreases (insert graph) [National Grid, 2006b]. Data collected on gas estimates is weather corrected, and is meant to reflect not only end-use demand, but storage and shrinkage [National Grid, 2006b].

Electricity consumption is also correlated with seasonal variations in temperature and climate, but mostly in the domestic sector, where consumption increases during the colder months and decreases during the warmer ones. Non-domestic electricity consumption follows a less dramatic pattern, with slight increases in use during the winter months in the commercial sectors, but virtually no change in the industrial sector (insert elec graph) [DTI, 2006b].

Overall energy consumption for 2003-2005 (all fuel types) follows similar seasonal patterns as described in the preceding electricity consumption analysis, with the domestic and services sector increasing use according to decreasing temperatures [DTI, 2006b]. Energy consumption within the industrial and transport sectors is little affected by seasonal climate variations, with changes over time more likely due to market forces.

Sources:

Boutet T S, *Controlling Air Movement: A Manual for Architects and Builders*, London, McGraw-Hill, 1987.

DTI, *Energy Trends: 2006*, Department of Trade and Industry, Stationary Office, Norwich, United Kingdom, December 2006b.

LCCP, *London's Warming: The Impacts of Climate Change – A Technical Report*, London Climate Change Partnership, Greater London Authority, London, 2002.

Mayes J, *South-east England*. In: Wheeler, D. and Mayes, J. (Eds.) Regional climates of the British Isles, London: Routledge, 1997.

Met Office, *Services for the Energy Industry*, Met Office, Crown Copyright, Web Page: http://www.metoffice.gov.uk/energy/index.html, Accessed: June 16, 2007.

National Grid, *Gas Transportation Ten-Year Statement 2006*, National Grid, 2006

National Grid, *Gas Demand Forecasting Methodology*, Accessed: webpage: November 2006b

LAQN, *Data Downloads: Wind Speed*, London Air Quality Network, King's College London,