Mass Retrofitting of an Energy Efficient Low Carbon Zone

A thesis submitted in partial fulfilment of the requirements of Edinburgh Napier University, for the award of Master by Research

Tosin Taiye Oye

March 2017

Director of Studies: Professor Mark Deakin

This thesis is dedicated to all the great teachers who instilled in me the joy of learning, my parents, brothers, sisters, and especially Blessing.

Declaration

To the best of my knowledge, this thesis contains no copy or paraphrase of work published by another person, except where duly acknowledged in the text. This thesis contains no material which has been previously presented for a degree at Napier University or any other university.

Abstract

By way of urban morphology, the design, layout and texture of district centres, neighbourhoods and buildings have as much a bearing on levels of energy consumption and rates of carbon emission as either buildings or their occupation: these recent discoveries propose urban morphology matters and both the design, layout and texture of district centres, neighbourhoods and buildings are as significant in setting levels of energy consumption and rates of carbon emission as the occupation and use of such structures. This thesis aims to reinforce this message and demonstrate how urban morphology does make a difference. Not only with respect to the geometry (i.e. surface and volume of the building design typologies), construction systems, or occupational behaviours, that such studies drawn particular attention to, but with regards to a matter which has been previously ignored. That is with regards to the potential which the planning, (re)development, design and layout of district centres and their neighbourhoods as context-specific transformations have, to not only lower levels of energy consumption and rate of carbon emission, but to uncover the significance of and particular contribution renewables makes to the mass retrofit proposals currently underway across Europe.

The approach this thesis presented adopts a key-component-based analysis of renewables in mass retrofit proposals and procedural modelling the geometry of this urban morphology is founded on. As an exercise in procedural modelling, the key component analysis also accounts for the renewables of mass retrofits in relation to the context of the application and with respect to the urban from of the buildings and their integration into the proposal. This in turn allows for the findings of this study to interpret the significance renewables take in the mass retrofit proposal, energy consumption and carbon emissions, it in turn generates as an energy efficient-low carbon zone and able to tackle global warming and combat climate change.

In this way, the thesis uncovers the significance of renewable as a source of clean energy in mass retrofit proposal and particular contribution it makes to levels of energy consumption and carbon emission. It means that for this thesis renewables are the key components of the mass retrofit it promotes to reduce levels of energy

consumption and lower carbon emission, vis-à-vis establish energy efficient-low carbon zones as an exercise in the development of sustainable suburbs whose status as city-districts not only tackle global warming but also combat climate change.

Content

Chapter One

Chapter Two

List of Figures

List of Tables

Chapter One

1.1 Background Introduction

Mass-retrofitting can be defined as the process of improving energy performance through adaptation and renovation at a community scale. It often involves modifications to existing commercial buildings that may improve energy efficiency or decrease energy demand (Deakin *et al.,* 2012a, 2012b). Also, mass retrofitting can be referred to the addition of new technology or features to older systems by improving efficiency, increasing output, reducing emissions and refining existing buildings with energy efficiency equipment at a community measure. In addition, retrofits are often used as opportune time to modify existing equipment or structures with additional or new components or members and provides the opportunity to achieve significant carbon savings (Deakin *et al.,* 2012, 2014; Richard P. 2016).

Research suggests that 40% of the UK's energy consumption and carbon emissions are caused by buildings energy use. Reducing emissions from buildings, by making them more energy efficient, is an important goal of urban planning. The energy consumption of buildings is dependent on a variety of parameters which are partly correlated (Edwards, 2009; Hetherington *et al.,* 2010; DECC, 2013). Ratti *et al.,* (2005) outline four main parameters which affect building energy performance: urban geometry, building design, systems efficiency, and occupant behavior. There are many energy performance software and models, which allow the analysis and simulation of buildings' behavior. However, most of them focus on single buildings and therefore are unable to analyze urban areas as a whole. Also, Ratti *et al.,* (2005) suggests these models are insufficient calibrated to study the energy performance of buildings, because they disregard the effect that urban geometry has on energy performance.

The analysis of Bourdic and Salat (2012), who compare different approaches to the measurement of energy performance show that morphologic models achieve the most accurate results, because they take all scales (city, district, single building) into account. According to Bourdic and Salat (2012), energy performance analysis must cover the design, construction, use and occupation, for single buildings as well as for whole districts.

Research studies by (Ratti, Baker and Steemers 2005) offers an account of why urban morphology, design, layout and texture matters by way of and through what might be best described as a coded critique of how the “building scientist” approaches on the matter of energy performance. By way of and through a coded critique of the approach which assigns buildings a set of values to be read-off by type of design, system of construction and occupant behavior independent of their environment. This is because for (Ratti, *et al.,* 2005) such a scientific reading of the subject offers too narrow a perspective on the design of buildings, their construction systems and occupational behaviors as determinants of energy performance and for the simple reason it fails to explain the high degree of variance between the values assigned to them and those experienced in the field. For them putting this right (i.e. explaining this variance in energy performance in terms of the gap between theory and practice) means that this study needs to transcend the all too narrow perspective of energy performance offered by the building scientist and broaden it out so as to begin accounting for the significance of renewable processes at play in such determinations (Deakin *et al.,* 2014).

Ultimately, this means understanding the relationship that buildings have to their environment both by way of urban morphology and through the context-specific form which building design, construction systems, occupational behavior and renewable energy technologies takes on. This is because previous studies of this kind provide critical insight into the context-specific form of the building designs, construction systems and occupational behavior that is currently missing and which limits what is known about energy performance (Deakin *et al.,* 2012, 2014). Focusing on the design, construction and occupational performances within the cities of London, Toulouse and Berlin, they find that variation in the consumption of energy by building, system and behavior, is something which cannot be explained by way of surface to building volume ratios alone, but through the relationship the passive to non-passive areas of their district centers also have to one another as neighborhoods. Together they propose these geometries account for up to 10% of the variance in energy performance previously left unexplained (Deakin *et al.,* 2015).

As such, recent studies serve to confirm the maxim that urban morphology does matter and should be seen as an integral component of any energy performance assessment, because knowledge of their context-specific form can account for up to 10% of the variance between the assigned values of building designs, construction systems and occupational behavior. While this reaffirmation of urban morphology in terms of context-specific form offers a critical insight of some magnitude, it says little about how such knowledge of building design, construction systems, occupational behavior and renewable energy technology should be drawn on to start transforming either the neighborhoods, or district centers of cities of which they form an integral part (Deakin *et at.,* 2014). The urban morphology and context-specific forms this takes on should not be ignored and ought to be integrated into the design of buildings, construction systems and occupational behavior, so any further investigation of the topic are left none the wiser as to how this broadening out of the subject can achieve this. While (Salat 2009) and Bourdic *et al.,* (2012) have recently sought to develop the surface-to-building volumes and passive-to-non-passive area, more recent studies suggest they tend to be represented in strictly technical terms, distinct from either the social, environmental, or economic relationships. This is despite both authors clearly acknowledging the criticality of such measures.

Subsequently, several studies have clearly revealed that existing retrofitting have no morphological basis, geometry or physics for transforming urban districts, targeting energy consumption, carbon emissions and combatting global warming as part of a climate change adaptation. These studies go some way to highlight a serious fault in the line of reasoning building physics adopts to tackle global warming and combat climate change and need to ground mass retrofit proposals in the case-based reasoning, so as to found it on a more stable and secure procedural modelling approach.

According to Ratti *et al.,* (2005), the first step in improving the energy performance of buildings is to study and simulate their behavior. However, many energy models and techniques have been developed for this purpose in recent years. These models usually adopt the perspective of the building designer: they tend to consider buildings as self-defined entities, neglecting the importance of phenomena that occur at the urban scale. In particular, the effect of urban geometry on energy consumption still remains understudied and controversial.

- Hetherington *et al.,* (2010) make known that the Governments around the world are setting targets and legislating to reduce the carbon emissions related to the built environment. However, challenges presented by increasingly rigorous standards for construction projects will mean a paradigm shift in how new buildings are designed and managed.
- Deakin *et al.,* (2012a) suggests that retrofitting goes well beyond energy consumption, because retrofitting's greater potential goes lies in incremental adaptation, reuse and renovation. For in [master]-planning suburban properties, more significant reductions in carbon emissions can be achieved with a systematic mix of house types.

This tends to suggest the literature currently available on retrofitting is selective, offering only a partial knowledge of the subject and is insufficiently comprehensive to offer an integrated solution. The purpose for this being that it either focuses exclusively on new development, or because the publications currently available on the renewal and redevelopment of the existing stock concentrate on reductions in energy consumption and not carbon emissions. For this study, the significance of renewables are the key components of the mass retrofit exploration: it promotes to reduce levels of energy consumption and carbon emission, vis-à-vis establish energy efficient-low carbon zones as an exercise in the development sustainable suburbs. In achieving such an integration and systematically demonstrating how urban morphology does matter, not as a process of new build, but incremental change and adaptation in the design and construction of city-districts; this study draws from networks of innovation across Europe and goes on to examine renewables as a clean source of mass retrofit proposal, contextualized and built-out as the fabric of an energy efficient-low carbon zone.

1.2 Research Aim

The aim of this study is to unfold the significance of renewable energy source in the retrofit and uncover the key contribution it makes to the levels of energy consumption and carbon emission.

1.3 Research Objectives

i. To review the literature on mass retrofits
ii. To use the findings of this literature review as a basis to augment and supplement the procedural modelling currently available to render roof structures a principal component of mass retrofit proposals
iii. To calculate the solar-power these roof structures generate as sources of renewable energy, by supplementing building footprint data with height and slope information.
iv. To reveal what these renewable energies contribute to the development of energy-efficient low carbon zones as sustainable suburbs.

1.4 Research Question

i. What do renewables contribute to the mass retrofitting of an energy efficient-low carbon zone as "sustainable suburbs"?
ii. In what way do the neighbourhood district-centres of these "sustainable suburbs" impact on the post-carbon economy and how does this in turn combat global warming as part of climate change adaptation?

1.5 Research Hypothesis

The renewable energy of an energy efficient-low carbon zone is a key driver in the urban planning and development of "sustainable suburbs" and geometry of an urban morphology that not only tackles global warming but which also combats climate change.

1.6 Dissertation Structure

The following dissertation report will be structured as follows:

Chapter 1 – Introduction: This chapter will include a clear introduction to the background of the chosen topic, the logic behind the proposed research, the purpose of the research, the hypothesis of the research, the aims of the research, the objectives of the research and the structure of the research.

Chapter 2 – Literature Review: This chapter will consist of a critical appraisal of previous research and publications carried out in mass retrofits, energy efficiency of buildings, EU case studies, low carbon zones and renewable energy technologies. Variations in options and gaps in the research area will also be examined and are used as the basis for the approach of the research dissertation.

Chapter 3 – Methodology: The methodology consists of a justification of the research methods used to investigate the areas where varied options and gaps were previously highlighted including a description of reasoning for the research approach and method of analysis.

Chapter 4 – Analysis of result and findings: A clear presentation of results with analysis and interpretation of findings, exclusively in relation to the findings of the literature review.

Chapter Two

2.0 Introduction

2.1 Hackbridge Suburb

In 2009, the London Borough of Sutton, its partners and the community made Sutton the first ‘One Planet Borough’ by launching a One Planet Action Plan and committing to live within a fair share of the earth’s resources by 2025. Some of the most challenging environmental targets in the UK were set, and good progress is being made. ‘One Planet Living’ is a framework developed by BioRegional (a social enterprise and environmental charity located in Hackbridge). It incorporates ten principles of sustainability encompassing individuals, the community, businesses and the public sector (Deakin *et al.,* 2012, 2013, 2014).

The Hackbridge project has been chosen because it is identified as Sutton’s flagship sustainable community development. Thus, Hackbridge displays some major strengths but at the same time is an ordinary suburb. The development proposed in the area also offers an opportunity to ‘try out’ certain initiatives. Hackbridge contains the world renowned ‘BedZED’ (Beddington Zero [Fossil Fuel] Energy Development) where BioRegional are based (London Borough of Sutton 2008a).

Significant levels of regeneration are occurring within Hackbridge. A masterplan has been developed to create the UK's first ‘truly sustainable suburb'. Detailed plans include 1,100 new sustainable homes, more shops, leisure and community facilities, new jobs, sustainable transport including pedestrian/ cycle initiatives and improved networks and open spaces (Deakin *et al.,* 2013). The Council’s Core Strategy for planning was adopted in December 2009. The strategy contains a commitment for all new buildings constructed in Hackbridge from 2011 onwards to be zero carbon. The Hackbridge community are currently working on their Neighbourhood Plan as part of CLG’s Neighbourhood Planning Front Runners Scheme (London Borough of Sutton 2008b).

2.1.1 Zero Carbon Hackbridge

The London Borough of Sutton has committed to a 100% reduction in carbon dioxide emissions from buildings by 2025, with additional ambitious carbon targets for construction materials, transport, food and consumer goods. Hackbridge is the best place to pilot this zero carbon buildings target. In fact, research suggests that the following initiatives are already taking place in the area (London Borough of Sutton 2008a):

- Sustainability visits: Eco-auditors visited around 70 homes in Hackbridge in 2008 to advise them about sustainable living, focussing on energy efficiency.
- Hackbridge Low Carbon Zone: Part of Hackbridge is the location for one of the Greater London Authority's Low Carbon Zones. Residents are being provided with free energy audits, easy energy efficiency measures and are eligible for discounted insulation measures.
- Greening businesses in Hackbridge: The London Borough of Sutton secured ERDF funding to deliver a programme of sustainability support for the businesses in and around Hackbridge. BioRegional are delivering this work. Businesses are given one to one support on reducing energy, water and waste. So far 39 businesses in and around Hackbridge have had an energy audit undertaken. Organisation-specific environmental policies have been formulated for 18 of these businesses.
- A district heating network has been proposed and encouraged by the Local Authority and is being procured by the developer of the largest development site in Hackbridge. This may be supplied by waste heat from a nearby landfill site.

Subsequently, the UK Government set out a definition for 'zero carbon homes'; they must have zero net emissions from all energy use in the home over the course of a year. Similarly, consultation to add further detail on the definition of zero carbon and to extend it to non-domestic buildings was initiated at the beginning of 2010

(Hetherington *et al.,* 2010). Given the contribution from solar is limited to 6-7% approximately if we add the deep retrofit and solar components then the rest must come from offsite developments. However, a three-tiered approach for reaching net zero emissions is adapted by the Government, illustrated as a hierarchical triangle in Figure 1.

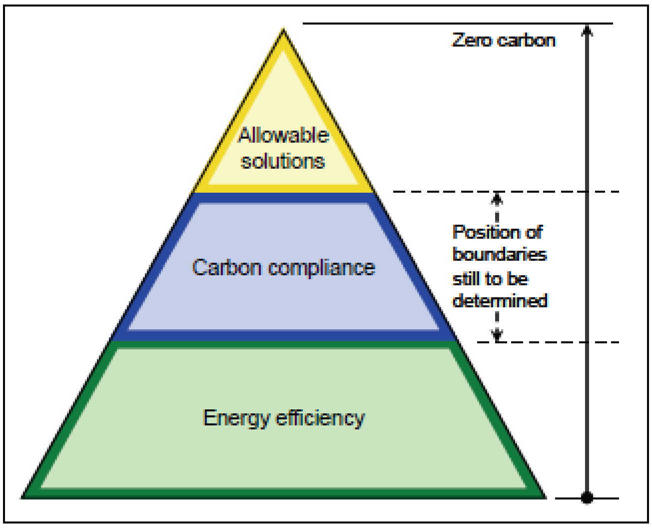


Figure 1: Hierarchy of permissible methods to achieve zero carbon developments. ***Source:*** Zero and low carbon buildings - A driver for change in working practices and the use of computer modelling and visualization.

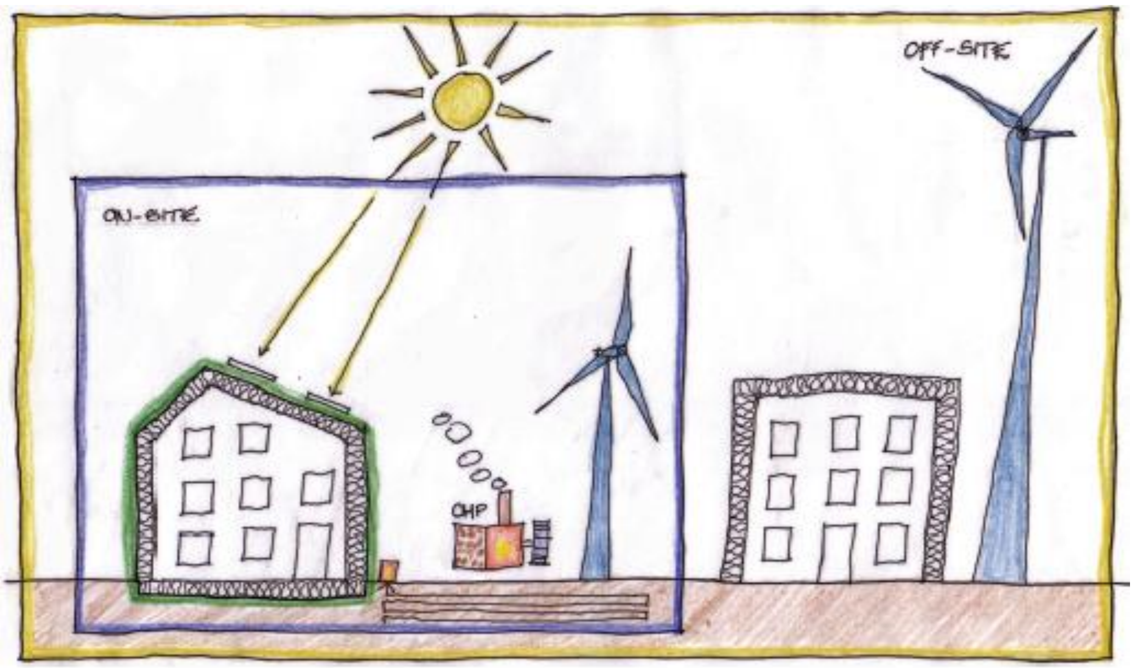


Figure 2: On-site and off-site compliance (Hetherington *et al.,* 2010).

The position of the boundaries between the areas of the triangle in Figure 1, that is for example, the percentage allocated for ‘Allowable solutions’, are still being debated.

In the light of this, Deakin *et al.,* (2012a, 2012b, 2013, 2014) developed the approach for such a base-lining exercise and applied it to Hackbridge where it was found that the task relates to environmental profile which this adaption strategy is based on. It is discovered wanting for the simple reason the Energy Options Appraisal is not clear as to whether the energy savings and carbon reductions generated from the forecast rates of consumption and emission will be spread equally amongst all occupants.

Previous studies by Deakin *et al.,* (2012a) also took the opportunity to undertake an extensive appraisal of mass retrofit methodology, to establish the nature and extent of current ‘state-of-the-art’ applications. In adopting Hackbridge as an innovative case study, Deakin *et al.,* (2012a, 2012b, 2013) analyzed not only the potential impact of the project in terms of reducing energy consumption and carbon emissions, but also considered the ‘institutional arrangement’ underpinning the mass-retrofit proposals. In developing a comprehensive profile of Hackbridge, Deakin *et al.,* (2013, 2014) raised questions as to the equitable distribution of benefits arising from the venture. In particular, concerns raised as to the potential divisiveness of the projects participation criteria which, at present, excludes the social rented sector from involvement in the venture. Deakin *et al.,* (2014) have identified this discriminatory approach undermines the project’s mandate of promoting environmental sustainability, in that it only serves to accentuate socio-economic discrepancies between resident groups.

2.1.2 Sustainability

Several studies illustrated that zero-carbon legislation does not specifically mention sustainability. It is, however, included in the BREEAM [BRE Environmental Assessment Method] assessments and the Code for Sustainable Homes, which whilst not a legal requirement, can be a condition of public funding (Hetherington *et al.,* 2010). However, sustainability is concerned with many more issues in addition to the reduction of fossil fuels. The Brundtland definition of sustainability is *“meeting the needs of the present without compromising the ability of future generations to meet their own needs”* (World Commission on Environment and Development, 1987). This is now considered over simplistic. Elkington (1998) suggests that the triple bottom line of economic, ecological and social sustainability is considered better criteria for measuring organizational (and societal) success. In this instance, the BRE [Building research Establishment] further describes it as “a complex web of systems and cycles in science, economics, politics, ethics and engineering” (Atkinson, 2009). In addition to the energy required to light, heat or cool, and run appliances within buildings in Hackbridge, Hetherington *et al.,* (2010) suggests there is energy to construct, refit and demolish it. This energy is embodied within the building. A sustainable approach, ‘cradle to cradle’, would have the buildings in Hackbridge reprocessed into another building, as shown in Figure 3.

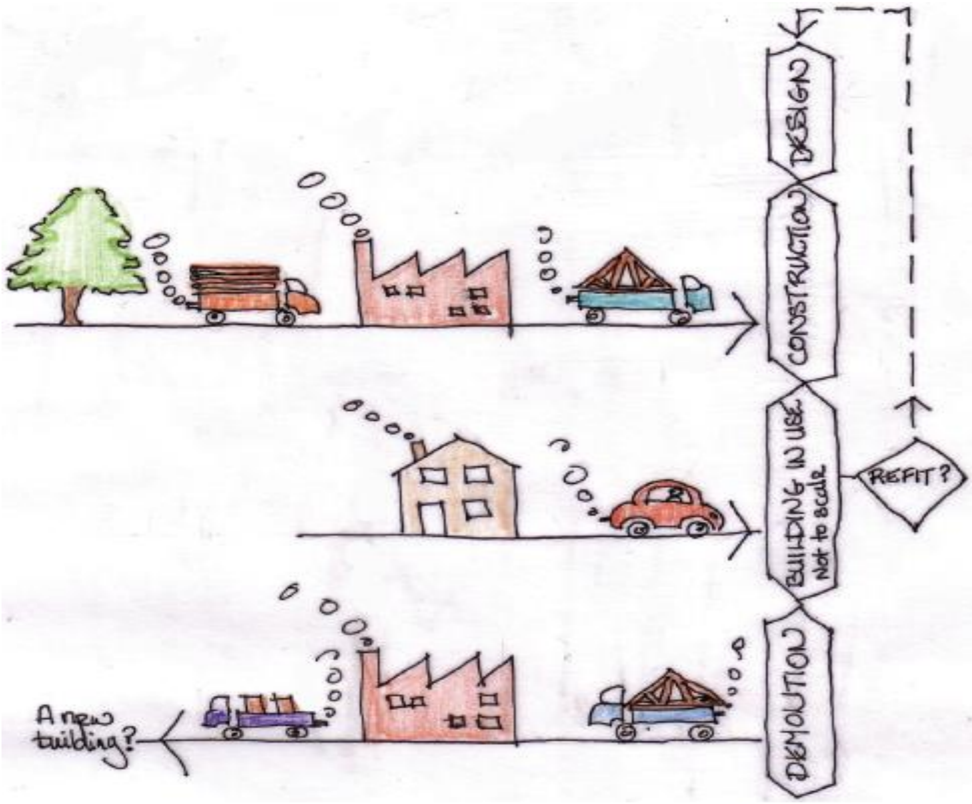


Figure 3: Sustainable building life cycle (Hetherington *et al.,* 2010).

Energy use is one important consideration of sustainable construction; there are many other life cycle considerations such as water resources, pollution, biodiversity, habitat, ecosystems. (Hetherington *et al.,* 2010). Whilst this research deals with mass retrofitting of an energy efficient low as a driver for transformation in Hackbridge, the larger picture should be borne in mind.

2.1.3 UK Building Emissions

Consequently, emissions from buildings accounted for 37% of total UK greenhouse gas emissions in 2012 (Figure 4). Residential emissions account for 66% of buildings emissions, with commercial and public sector emissions accounting for 26% and 8% respectively. They comprise 45% direct CO_2 emissions (i.e. from burning fossil fuels) and 55% indirect (grid electricity-related) emissions (DECC, 2013).

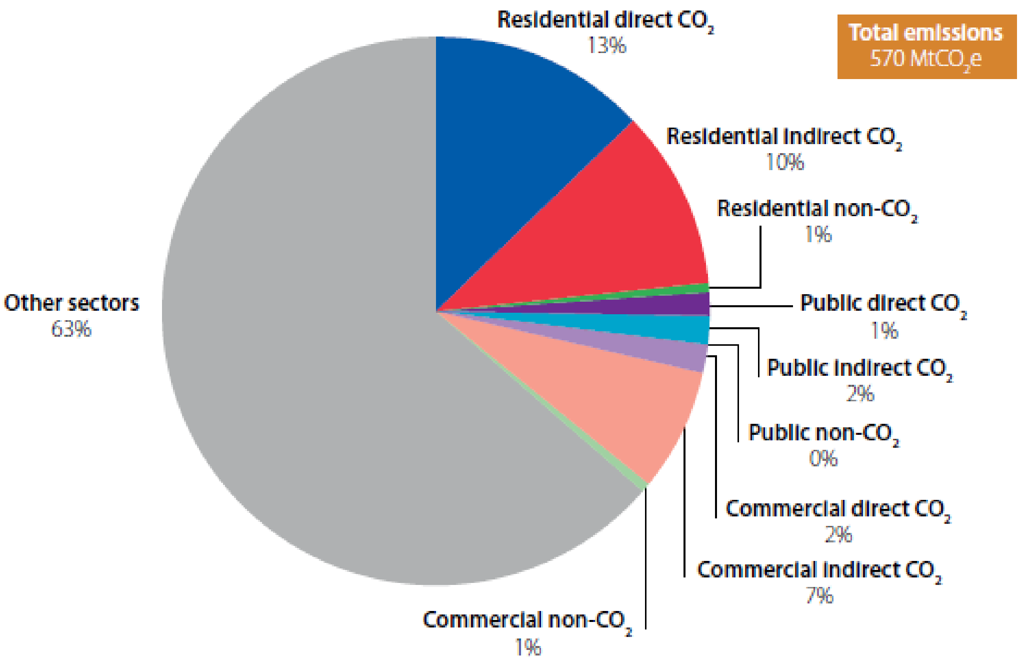


Figure 4: Emissions from buildings in the context of total UK emissions. ***Source:*** NAEI (2015), DECC (2013), Energy Trends, March 2013, DECC (2012) DUKES; CCC calculations.

Between 2003 and 2008, buildings CO_2 emissions fell by 3%, mainly due to improved energy efficiency. Since 2008, buildings emissions have fallen by 8% but have shown year-to-year fluctuations due to economic and temperature effects, i.e.

while in 2009, emissions dropped 10% due to rising fuel prices and the recession, they increased by 7% in 2010 due to cold weather, but fell again (by 14%) in 2011 due to warmer winter months and rising fuel prices (NAEI, 2015). However, as part of the ambition of Sutton for buildings to be zero carbon by 2016 for residential buildings and 2019 for non-residential buildings, CO_2 emissions per square metre from 2013 will be at least 40% below the Notional Building emissions as defined by Building Regulations Part L 2010 NCM software; for this development, the figure has been set to 25% reduction in CO_2 emissions as defined in the Local Authority's decision notice. In the light of this, it is proposed that (DECC, 2013; NAEI, 2015).

2.2 The Study of Urban Morphology

Several studies define urban morphology as the study of the form of human settlements and the process of their formation and transformation. Also, it seeks to understand the spatial structure and character of a metropolitan area, city, town or village by examining the patterns of its component parts and the process of its development. This means understanding the relationship that buildings have to their environment both by way of urban morphology and through the context-specific form which building design, construction systems and occupational behavior takes on. This is because for Ratti *et al.,* (2005), urban morphology provides a critical insight into the context-specific form of the building designs, construction systems and occupational behavior that is currently missing and which overlooked what is known about renewables as a clean source of energy. Focusing on the design, construction and occupation of buildings within the cities of Berlin, Toulouse and London, Ratti *et al.,* (2005) find that variation in the consumption of energy by system and behavior of the occupiers, is something which cannot be explained by way of surface-to-building volume ratios alone, but through the relationship the passive to non-passive areas of their district centers and neighborhoods also have to one another. Together they propose these geometries account for up to 20% of the energy performance, with building designs, construction systems and occupational behavior making up the other 80%.

Nevertheless, the background research to the study of urban morphology by Ratti *et al.,* (2005) is based on March's (1972) analysis of building heat loss, Owens' (1986) extension of this across house types and the augmentation of this by Steadman *et al.,* (2000) to cover the non-domestic sectors. All of this is in turn captured and represented in Steemer's (2003) study of energy consumption within cities and in relation to the density of buildings alongside their associated mobility and transportation networks.

Against this backdrop, Ratti *et al.,* (2005) explore the effects of urban texture on building energy consumption. Their work is based on the analysis of Digital Elevation Models (DEM) in Paris, London and Toulouse. In these studies, the DEMs are stored in a 2D-Matrix with height values and processing tasks constructed by means of MatLab software. Building energy consumption in general is dependent on many parameters which are partly correlated with each other. Ratti *et al.,* (2005) outline four main parameters which impacts upon energy performance. Highlighting urban geometry, building design, construction systems and occupants' behavior as the "four parameters of energy performance", their study aims to loosen the grip buildings have on energy performance by way of and through analysis of the geometric form they take. In loosing this grip and highlighting all four parameters of energy performance, Ratti *et al.,* (2005) draw attention to two ratios whose geometric form set the parameters for the other three (buildings, construction systems and occupational behavior).

The first ratio draws on the earlier research of March (1972) which arose from the question: "which shape should a building have to minimize heat loss?" For his building design model March (1972) assumes that its shape is perfectly rectangular, that thermal transmittance is equal through all external walls and there is no heat transfer from the building to the ground. This is referred to as the *surface-to-volume ratio* (STVR) and value which is calculated by dividing the overall building envelope area (without ground area) by the volume. However, Ratti *et al.,* (2005) suggest the STVR is not a very good indicator of energy performance, because only heat lost through the exposed building envelope is measured, while any gains from the use of natural ventilation and sunlight for heating and lighting purposes is ignored.

Taking the limitations of the STVR into account, Ratti *et al.,* (2005) advance another ratio that sub-divides buildings into passive and non-passive areas. Here passive-areas measure the parameters of buildings lying within six meters of the façade or within twice the ceiling height. These passive-areas gain from natural ventilation and sunlight, whereas non-passive areas do not. The ability buildings should use natural ventilation and sunlight is referred to as the *passive-volume-to-total-volume ratio* (PVTVR). This ratio is another attempt to analyze the geometry of a building's energy performance and its limitations are also drawn attention to. This is because passive areas can still be wasteful, as mechanically lit their ventilation and glazing ratios may be very low, allowing heat loss through external walls and roof spaces to be greater than gains from sunlight.

Seeing that only an integrated energy model can overcome such limitations in the measurement of energy performance, Ratti *et al.,* (2005) make use of the LT-method (light and thermal method) to calculate the annual heating, lighting, ventilating and cooling of buildings in terms of use/m^2. This model considers a variety of factors, including solar gains, shading of a neighbor's house (indicated by the obstruction sky view) and degree of daylight that is either reflected from opposite facades (information about the orientation of facades is needed to calculate this) or which is directly received from the sun. The LT-method is applied by Ratti *et al.,* (2005) to analyze the energy performance of blocks, neighborhoods and districts in the cities of London, Toulouse and Paris. The findings of these studies are held up as examples of how urban morphology has a bearing on energy performance when analyzed in terms of both the STVR and PVTVR values for the "blocks, neighborhoods and districts" of the building designs, construction systems and occupational behaviors under investigation.

Consequently, Deakin *et al.,* (2013) demonstrates how urban morphology does matter in the perspective of reaching beyond the geometry of building design, construction systems and occupational behaviors and towards broader context-specific transformations. Similarly, Deakin *et al.,* (2014) go on to demonstrate how urban morphology matters, by way of and through what might be best described as a coded critique of how the "building scientist" approaches the matter of energy performance. More importantly, by way of and through a coded critique of the approach which assigns buildings a set of values to be read-off by type of design, system of construction and occupant behavior independent of their environment. However, while the aforesaid successfully extends urban morphology into the fields of carbon emission, global warming and climate change adaptation, it fails to highlight the role which renewables play in this transformation to sustainable development. This oversight is important to correct because it clearly fails to recognize the contribution renewables make to sustainable development, and solar power as a clean source of energy with zero carbon emission.

2.2.1 London, Toulouse and Berlin Case Study

The data presented in Table 1 were collected in three DEMs that represent central areas in London, Toulouse and Berlin. Berlin has the minimum surface-to-volume ratio and therefore minimizes heat losses; London and Toulouse follow. The increase can be as large as 45%, a figure that suggests a potentially significant energy impact. However, a question arises: is it correct to aim to minimize the exposed surface of buildings? If this principle were accepted, the best shape to accommodate all the volume of the London case study site would be a March halfcube (or a full cube if ground losses are taken in to account).

Table 1: Data for London, Toulouse and Berlin (Ratti *et al.,* 2005).

	London	**Toulouse**	**Berlin**
Ground floor area (m^2)	89,663	64,368	55,978
Un-built area (m^2)	70,377	95,632	104,022
Built volume (m^2)	1,221,499	966,768	1,042,199
Vertical surface (m^2)	174,757	174,888	119,698
Surface to built volume ratio (m^{-1})	0.216	0.248	0.169
Average energy consumption in passive & non-passive zones (KWhm/p.a.)	0.0683	0.0668	0.0731
Average energy consumption in passive zones (KWhm/ p.a.)	0.0590	0.0599	0.0585
Average energy consumption in passive zones with optimum glazing ratio	0.0554	0.0568	0.0550

(KWhm/p.a.)			

In another case study, Salat (2009) compares the urban morphology of Paris with the energy consumption of building designs. This analyses the impacts which the types of urban morphology factors listed below have on building designs, construction systems and occupier behaviors in terms of energy consumption and CO_2 emission.

- Mean and standard deviation of building height
- Mean and standard deviation of vegetation height
- Building height histograms
- Area-weighted mean building height
- Area-weighted mean vegetation height
- Surface area of walls
- Plan area fraction as a function of height above the ground surface
- Frontal area index also as a function of height above the ground surface
- Height-to width ratio
- Sky view factor
- Roughness length
- Displacement height
- Surface fraction of vegetation, roads, and rooftops
- Mean orientation of streets

In this case study, 96,000 residential buildings are analyzed and five key components of energy consumption are calculated in accordance with the contribution they make to levels of CO_2 emission. The key components, derived from this case study, along with their factor contributions are set out below:

- Efficiency of urban morphology (e.g. density) (1.8)
- Building design performance (e.g. shape, envelope area) (2.5)
- Efficiency of construction systems (e.g. age of boiler) (1.8)
- Occupants behaviour (2.6)

Under this factor-component model, the city is represented as a homogenous entity where urban morphologic values, such as density, mobility-networks and accessibility are related to one another. Like Ratti *et al.,* (2005), Salat (2009) sees the ultimate value of this model lying in the ability it must isolate the contribution urban morphology makes to energy performance when measured in terms of either the STVR or PVTVR. For in the case of Paris, the ratios calculated and drawn upon as measures of energy performance, suggest the traditional, dense-built courtyards of this city have a good STVR and PVTVR. Good in the sense that unlike their modern counterparts, which are characterized as dispersed low-density developments and found in the suburbs of Paris, these offer building designs, construction systems and occupational behaviors which illustrate poor STVR and PVTVRs. However, the following statement from Bourdic *et al.,* (2011: 483) goes some way to clarify the position adopted. As is stated: "our [position] is embedded in the factor approach to reducing resource consumption traduced by Ernst von Weizeacker in his book: Factor Four: Doubling Wealth, halving Resource use. He starts from the principle that reducing our energy footprint can be facilitated by breaking down into factors, each which can examined separately as a lever for action. Ratti *et al.,* (2005), adopted this concept specifically to the urban environment in the factor breakdown shown. Urban morphology can contribute to halving energy consumption and greenhouse gas emissions. In this system of indicators, attention is focused upon the morphological aspects that follow from the principles developed and which will take up building technology to a certain extent, being that it is sometimes hard to separate the latter from the former, and that the latter is essential when it comes to measuring the energy consumption of a district and city".

Having made this statement, Salat (2009) goes on to highlight the significance of this "focus on morphological aspects" further by characterizing it as distinct from and as opposed to matters of "building technology", while configuring the former as to "take-up" aspects of the latter. This process, whereby the former takes up the latter and this is then singled out as an "essential", component of any such factor analysis, especially when it comes to measuring energy consumption and carbon emissions".
The model illustrated in Figure 5 serves to indicate how this is possible. As can be seen it represents morphology as the extreme boundary of the energy performance

model. An energy performance model whose boundaries which in turn are seen to capture the thermodynamic and constructed tendencies, ecology, exergy, entropy and fractal geometry that make up the complex (invariant) structures (in this instance, highly structured, resilient and adaptive systems) subsequently advanced as the area-based, vis-a-vis spatial “scales of analysis” illustrated in what is referred to as a “Pareto distribution” of this configuration. This in turn gives rise to the morphology of large scale assessments that cover cities, their districts, neighbourhoods and blocks and which in turn capture smaller scale equivalents rendered in terms of buildings, systems and behaviours. However, Salat (2011: 484) goes on to further bestow the virtues of this model by suggesting it: “responds simultaneously to social needs – by improving the day-to-day quality of life of residents – to environmental objectives – by reducing resource and energy consumption – and to economic considerations – by valorizing places, fostering activities and saving money through the reduction of resource and energy use.”

In view of the potential which exists to save energy and reduce carbon emission by as much as 50%, Bourdic *et al.,* (2012) stress that to capitalize on such virtues, save energy, reduce carbon emissions and sustain development, stakeholders need robust methods capable of assessing such possibilities. As they point out: many tools and assessment methods have been developed to improve energy performance. However, as Bourdic *et al.,* (2012) also goes on to stress: most of these methods are still based on the building envelope and given stakeholders are now convinced the so-called “building scientist” approach is too narrow to capture the role urban form plays in the determination of energy performance, these assessments now need to be extended so they can cover the buildings, systems and occupants of both the blocks, neighborhoods and districts of cities.

The reason Bourdic *et al.,* (2012) reiterate this message is not immediately clear, but is important because it throws much-needed light on what the calculation of the STVR and PVTVRs for Berlin, Toulouse, Paris and London offer in terms of energy performance. For what they offer is ‘proof of concept’ and evidence as to the significance of urban morphology as a key component of energy performance. That is as a key component of energy performance that not just matters, but which should also be considered alongside the building design, construction systems and occupational behaviors of any such determinations. Alongside and therefore in conjunction with the buildings, systems and occupancy components which determine energy performance. For only in this way is it possible to account for the 20% of energy performance which relates to urban morphology, but other factor weightings that make up the remaining 80% of the total measure (Deakin *et al.,* 2015).

This is perhaps why Bourdic *et al.,* (2012) go on to review the potential there is to integrate their urban morphology model of energy performance with those adopted to assess buildings, systems and occupant determinations. For this purpose, the nested configuration of urban morphology is set aside and the “common six-step analytical grid” first developed by Ratti *et al.,* (2005) is then augmented by Bourdic *et al.,* (2012) so this model of energy performance can be used as an assessment system.

2.2.2 Factors that Affect Energy Consumption in Buildings

Figure 5 sets out the six-step analytical grid first developed by Ratti *et al.,* (2005). This analytical grid in subsequently augmented by Baourdic *et al.,* (2012) to classify the types of ‘calculation tools’ such models and assessment systems should adopt. This ‘grid of calculation tools’ is then applied to review the strengths and weaknesses of these assessments. Bottom-up, agent-based models are under-determined at anything more than the building scale (i.e. block, neighborhood, or district), whereas the economic models are too top-down and therefore over-deterministic. Likewise, energy-environment models are being too aggregated, overly analytical and stuck in the diagnostic stage of development. For this suggests it unable to provide any information on the intervention mechanisms which are available to improve buildings energy efficiency and cut carbon emissions.

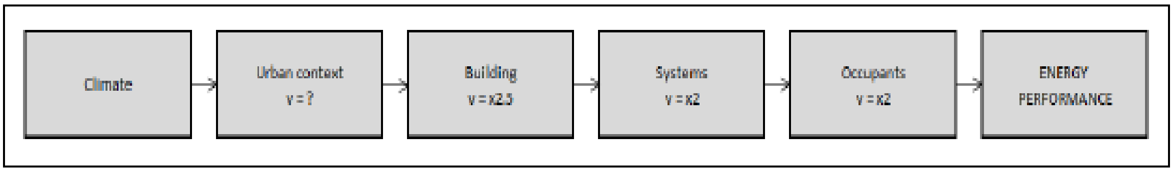


Figure 5: Factors that affect energy consumption in buildings (Ratti *et al.,* 2005).

Turning to the morphologic models, Bourdic *et al.*, (2012: 522) state these models: "significantly differ from the three other types described above. While morphological approaches to quantify energy consumption and carbon emissions for the building sectors remain rare, two are analyzed here: one is limited to the residential sector, the other to commercial buildings (Yamaguchi, 2003). Both are based on a scale that is larger than the individual building and aim to account for the interactions between buildings. These are the only methods that explicitly consider the district or city as a whole, as opposed to the sum of the individual buildings".

As they go on to say: "these models provide aggregations which consider all the scales that constitute the urban fabric of buildings, blocks, neighborhoods and districts. By using intermediate scales of aggregation, the loss of information in the process is structurally lower than with other models. They provide them an undeniable operationality to monitor the impact of energy performances on several scales."

The only downside of these models is seen by Bourdic *et al.,* (2012) to lie in the fact they are restricted to the context of buildings and do not extend into either the energy systems, or occupation components of energy performance. Taking this form, the review from Bourdic *et al.*, (2012) serves to capture the state-of-the-art on the types of building energy models drawn attention to by the likes of Ratti *et al.,* (2005) and urban morphology approach to the fabric of buildings, blocks, neighborhoods and districts highlighted by Salat (2009) and Bourdic *et al.,* (2012). However, it also serves to highlight the fact that current state-of-the developments still leaves the four main components of energy performance only loosely coupled in these models and lacking the systematic integration which is needed for this requirement to be fully accounted for.

Reflecting on this development, Bourdic *et al.,* (2012: 529) go on to state: “it is probable that no single model or calculation tool will succeed in considering these four factors at the same time. Therefore, research efforts should focus on the inter-actions and relationships between existing models. Transversal approaches based on existing models and tools may lead to a more systematic and comprehensive understanding of urban efficiency, making good – or at least better – use of all of the intervention opportunities”.

In responding to this challenge, they go on to advance an innovative system of indicators that in their opinion meet the call for multi-scalar and cross-cutting indicators which encompasses the intrinsic complexity of the situation. Based on this morphologic approach, new mathematical formulas are used to generate urban sustainability indicators. They suggest these indicators can assist with the comparison of urban projects by structuring them into techniques of analysis capable of assessing energy efficiency, alongside and in conjunction with the social and environmental components of urban development.

Figure 5 provides an extract sample of indicators, by type and triptych (sustainable urban development as the environmental, social and economic pillars of climate change) adopted to capture the morphology of city-districts. The urban morphology, typology and grids they present are said to be ‘exceptional’ and of particular value because: “while some governments are committing themselves to reducing energy consumption and carbon emissions, they need tools to measure the current performance of their cities, to find the levers to reduce it and to assess the efficiency of the actions engaged. Therefore, assessment systems play such a key role. However, cities are incredibly complex systems, made of components that can be identified using different point of views. Assessments based on single or simple metrics such as energy flows are insufficient to address the wider socio-ecological aspects of cities.” (Bourdic *et al.,* 2012).

2.2.3 The Principal Component of Mass Retrofit

Figure 6 sets out the standard morphologic model first advanced by Ratti *et al.,* (2005) and serves to reaffirm the relationship between climate and what are referred to as the four structural (context, buildings, systems and occupational) components of urban energy performance. It does this by overlaying the model with the components Bourdic *et al.,* (2012) offer. For here the application of the Digital Elevation Model (DEM) to analyze the context is represented, along with the tools for analyzing the buildings found within the respective forms, shapes and envelopes. This in turn draws attention to the themes that make up the systems and triptych (sustainable development) of their use and occupation.

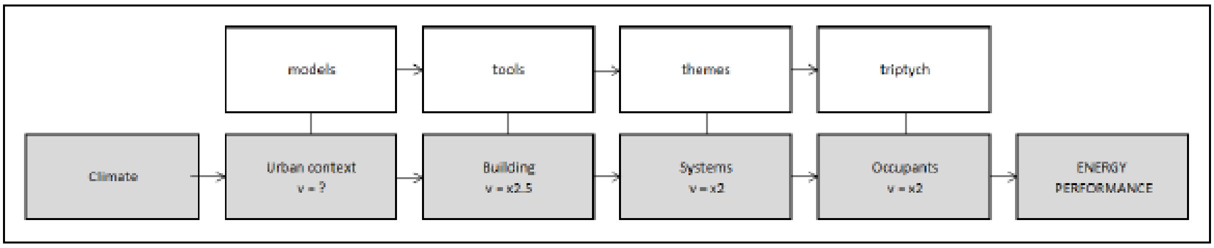


Figure 6: Factors that affect energy consumption in buildings (Deakin *et al.,* 2014).

Figure 7 develops this representation further. This begins by setting out the pretext to the interest in climate change and application of the morphologic models set out here as part of an adaptation strategy. Here particular attention is drawn to the mass retrofitting of an energy efficient-low carbon zone as a sustainable suburb both by way of an urban regeneration strategy and through the visions, master-plans and development scenarios such a transformation is based on (Deakin *et al.,* 2014). Moving from top-to-bottom, this in turn indicates the Lighting and Thermal Method (LTM) is supplemented with a 3D rendering of the context grounded in ArchGIS technologies and Google maps. Also, Deakin *et al.,* (2015) suggests this represents a context that is underpinned by an analysis of the social needs and material requirements which such a demographic imparts on an information system. On an information system, whose ecological, exegetic and entropic qualities supports the physical form, shape and envelope of both the densities and mass of geometries which are placed under examination (Deakin *et al.,* 2015).

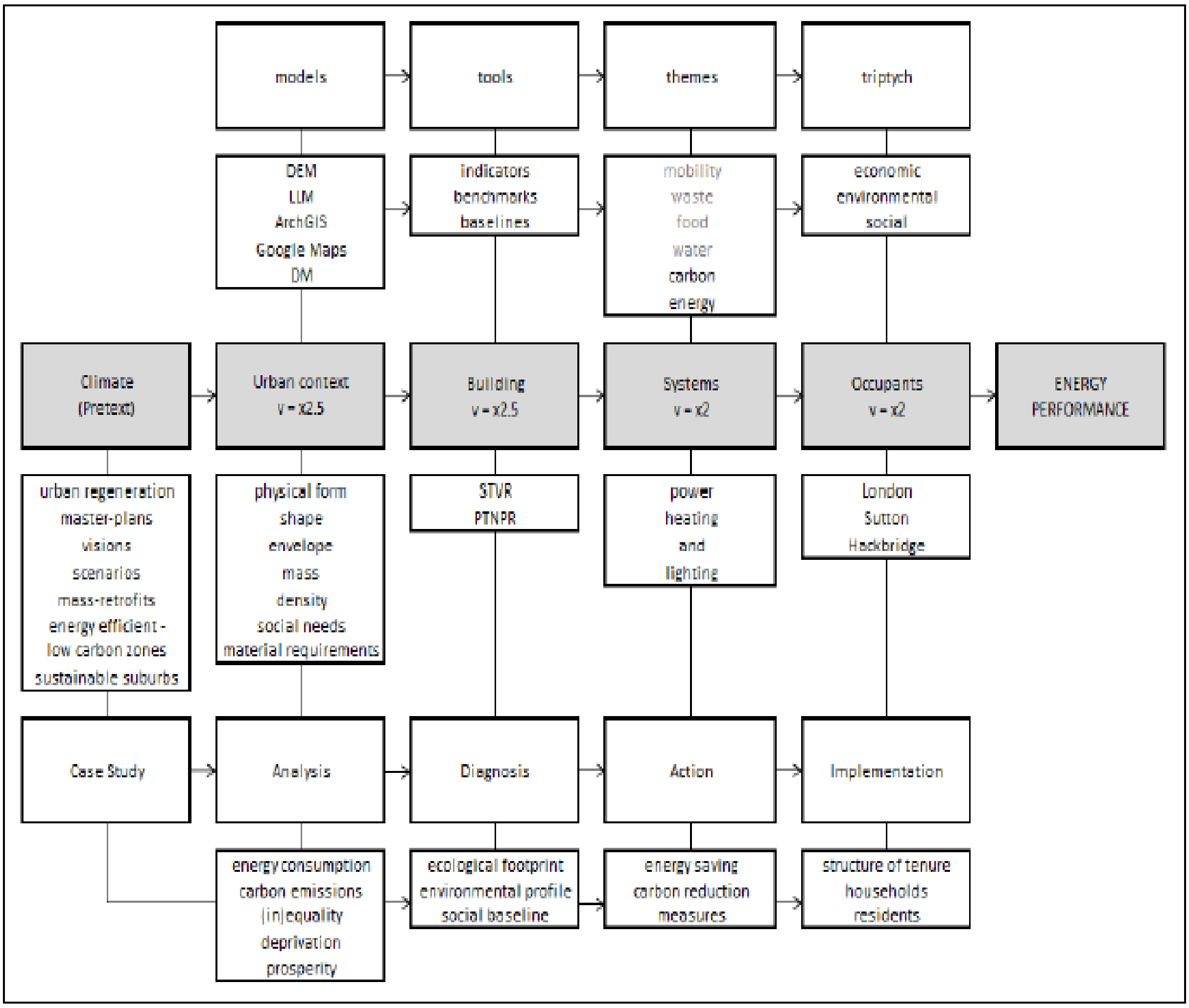


Figure 7: Factors that affect energy consumption in buildings (Deakin *et al.,* 2014).

According to Deakin *et al.,* (2014), the next column in this representation draws attention to the tools available to indicate, benchmark and baseline the STVR and

PVTVR of the blocks, neighborhoods and districts under examination. This in turn leads to the themes (energy, carbon, water and mobility issues) linked to the power, heating and lighting systems central to mass retrofit proposal. Likewise, Deakin *et al.,* (2015) suggest the final column highlights the triptych in terms of the social, environmental and economic sustainability of those occupying this energy efficient-low carbon zone.

Under this rendering of the material lies a further level of case-study analysis. This focuses attention on the diagnosis, action and intervention of urban planners, architects, designers and building contractors in Hackbridge and those promoted in the interests of securing the transformation of Sutton into a sustainable suburb (Deakin *et al.,* 2015).

2.3 Effect of Urban Morphology on Energy Consumption

Several studies suggest that impact of urban morphology on the energy consumption of buildings mainly relates to the availability of sunlight and daylight on buildings. Albeit solar energy as a major source of renewable energy can be used to make buildings more energy efficient and reduce carbon emission. In this essence, solar energy can be used in terms of passive solar gains or converted into renewable energies. Cities offer a huge solar resource which is mostly unexploited.

Upon other factors influencing energy consumption, such as occupant behavior, sun patterns and energy received from the sun are predictable. Thus, question arises in several studies about how the availability of sunlight is affected by urban forms. However, it is established that the energy performance of denser cities is better, regarding morphological indicators. On the other hand, how does for instance density of buildings affect the solar potential? In this logic, the calculation of solar radiation as part of the morphological analysis of 3D city models at urban scale can provide a deeper general understanding of the energy performance of cities.

Previous studies by Carneiro *et al.,* (2009) examined morphological indicators that provide information about how different urban models behave in terms of solar energy. As a matter of fact, their investigation offers the estimated solar radiation for two pilot zones in Geneva. Albeit the first is an historical district with a dense fabric and few open spaces while the second is a modern district that has a lower density, smaller buildings (two stories high) and more open spaces. Also, Carneiro *et al.,* (2009) analyzed built volume, mean built height, theoretical population, urban built density and ground coverage as morphological indicators. For these measures asses, the SVTR to quantify the compactness of a district. While the first district is more compact than the second district, the results in terms of irradiance are similar for both urban morphologies. In this essence, Carneiro *et al.,* (2009) states that "nevertheless the production of solar energy on low density areas is easier due to less urban obstructions and a lower population density. The lower population density combined with the building typology results in more potential solar roof area per person".

2.3.1 Solar Radiation

The sun is the primary source of energy for life on Earth. However, solar energy is the result of a nuclear fusion at the core of the sun. This results in a surface temperature of around 5,800 Kelvin. The spectrum of emitted electromagnetic radiation from the sun is like that of a 5,776 K blackbody, whereby around 50% lies in the infrared region, around 40% in the visible region and approximately 10% in the UV region (Sun *et al.*, 2003). The total amount of radiation released is approximately 63,000,000 Watts per square meter (W/m^2) (Pfidwirny, 2006).

According to Muneer (2004), solar radiation data is usually given as the amount of energy received on a horizontal surface. However, Sun *et al.*, (2003) suggests that the amount of extra-terrestrial irradiation reaching the earth's atmosphere, at the mean earth sun distance of 149,597,890 km, is called the solar constant. It is calculated from long-term measurements to be around 1366 W/m^2. By means of entering the Earth's atmosphere, solar radiation is absorbed and scattered as shown in Figure 8. The radiation reaching the surface unobstructed is called direct (beam) radiation. However, it is responsible for casting shadows as the rays are still collimated and can be blocked by an object. For radiation scattered by atmospheric gases, aerosols, clouds and the Earth's surface is called diffuse radiation. (Sun *et al.*, 2003).

Muneer (2004) suggests that diffuse and direct radiation combined result in the global radiation on a surface but tilted surfaces in contrast to horizontal surfaces receive a combination of direct, diffuse and additional reflected radiation from surfaces. In urban areas, this component can be quite significant.

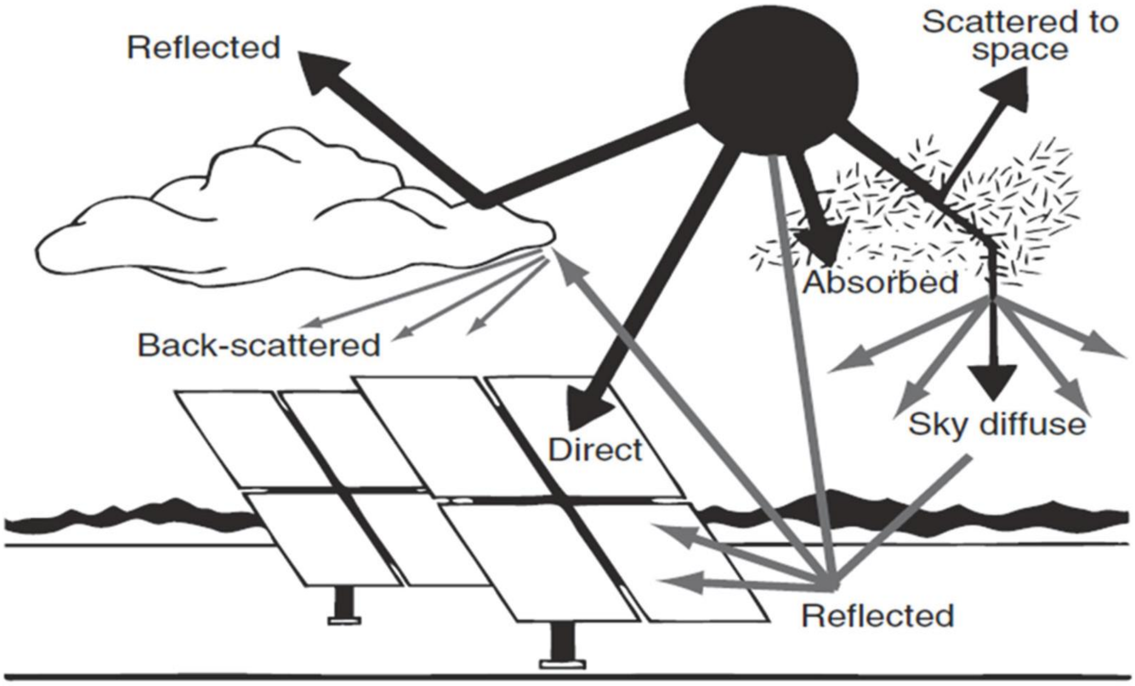


Figure 8: Segregation of solar radiation by the atmosphere (Badescu, 2008).

According to Badescu (2008), the difference between global solar radiation at the Earth's surface and the corresponding value at the top of the atmosphere is, what has been absorbed or reflected away. Also, this difference is referred to as the Earth's albedo and about 29% of the incident solar radiation. However, the total amount of solar radiation incident on a given surface during a specified period is called insolation or solar irradiation. For each site on the Earth surface, the received insolation differs as a function of the Earth's geometry and geographical conditions. Studies suggests these factors can be grouped in three categories (Suri and Hofierka, 2004):

1. Global - The Earth's geometry, revolution and rotation

2. Regional - Terrain

3. Atmospheric attenuation

2.3.2 Global Factors

On a global scale, the relative position of the Earth to the sun strongly influences the amount of radiation the Earth's surface receives. By means of using astronomical formulas, the available radiation can be precisely calculated (Suri and Hofierka, 2004).

Thus, the Earth rotates around its own axis, causing daily cycles of day and night. Also, the Earth's rotation axis is tilted at 23.5°, known as declination. On its orbit around the sun the relative position of the Earth's axis to the sun changes. The tilt is toward the sun (June +23.5°) or away from the sun (December -23.5°) (Grondzik, 2010). This variation is responsible for the annually changing height of the sun above the horizon and controls the length of the radiations path through atmosphere, which are determining the duration and intensity of solar radiation received on the Earth's surface. Therefore, the tilt causes the seasons, with the altitude of the sun being the highest in summer and lowest in winter.

For any point on the Earth's surface, the position of the Sun is defined by its altitude angle and azimuth angle. The altitude angle specifies the height of the sun in the sky above the horizon. At sunrise and sunset, the altitude is 0°. It reaches its daily maximum at solar noon. The altitude at solar noon varies throughout the year, reaching a yearly maximum on June 21 and its minimum at December 21. It depends on the latitude of the position and the tilt of the Earth and can be expressed by following equation (Grondzik, 2010):

Altitude angle at solar noon = 90° - latitude +- declination.

The azimuth angle, which is also affected by the seasons, is the angle between the position of the Sun and true south (Grondzik, 2010).

2.3.3 Regional Factors

At regional scale, the amount of available solar radiation incident on a surface is modified by the terrain, which causes high spatial and temporal differences in local values (Suri and Hofierka, 2004). Although modifying features have variations in elevation, the slope inclination and orientation, as well as shadows casted from neighbouring terrain features. More importantly, these circumstances can be modelled with a high accuracy, e.g. with a digital elevation model (DEM).

2.3.4 Atmospheric Factors

Previous studies suggest that the third factor is the above-mentioned absorption and scattering of solar radiation in the atmosphere. Albeit extra-terrestrial radiation passing the Earth's atmosphere is attenuated by atmospheric gases, aerosols and clouds, whereby clouds are the most important regulator of solar radiation with regularly 65% of the earth covered by clouds (Sun *et al.*, 2003).

In addition, maximum insolation is obtained when the sky is clean and dry. However, the influence of atmospheric attenuation can be calculated. Real-sky (overcast) radiation values consider all three factors, clear-sky radiation values (cloudless) omit the cloud attenuation (Suri and Hofierka, 2004).

2.3.5 Modelling Solar Radiation Estimates

While the understanding of solar energy incident on the building envelope is essential to improve the sustainability of urban settlements. Previous examination suggests that estimates of the spatiotemporal solar radiation distribution, and thereby information of solar radiation and its components at a location, allow to assess the potential of renewable energies. Also, the amount of solar energy incident on a surface is strongly determined by the surrounding terrain and features. However, varying elevations, aspects and shadows create strong local gradients in incoming radiation (Dubayah and Rich, 1995). For complex terrains, like urban settlements, these variations are significant for the insolation characteristic.

In addition, solar radiation can be measured by solar radiation monitoring stations on the ground. Albeit they provide accurate data which can be used to interpolate spatially continuous insolation values. For flat terrains and homogenous climatic properties, this technique produces satisfactory estimates. However, for more complex terrains, interpolation is unfitted (Tovar *et al.*, 1995).

Ruiz-Arias *et al.*, (2009) also suggests another way of obtaining area-covering insolation estimates is to derive them from satellite images. However, when compared to ground measurements these values are less accurate, particularly for cloudy sky conditions. Albeit an accurate and cost effective way to represent the spatial and temporal variability of insolation are spatially based solar radiation models.

2.3.6 Digital Elevation Model (DEM)

As recent research suggests that solar radiation models are usually implemented in a GIS environment and able to model the spatial distribution over various 2D surfaces. The underlying surfaces are represented by a raster data model, typically a digital elevation model (DEM) (Ruiz-Arias *et al.*, 2009).

In addition, DEMs contain continuous elevation values over a topographic surface. These elevation data include the terrain, as well as buildings, trees and other features. DEM based models determine regional factors on solar radiation (elevation, surface orientation, shadows) at every point of the DEM (Ruiz-Arias *et al.*, 2009). While estimating the solar radiation for each point of the DEM, the radiation incident on a level surface at the point is modified considering the regional factors (Dubayah and Rich, 1995).

The outputs of DEM-based radiation models are affected by the resolution of the DEM. For different resolutions, the calculations of elevation, orientation and shadows will differ. That effect is intensified with an increasing complexity of the terrain. A finer spatial resolution of the DEM also increases the calculation time (Ruiz-Arias *et al.*, 2009).

2.3.7 3D – Models

Recent studies indicated that the availability of 3-D city models, representing complex urban morphology, is steadily increasing. Likewise, the analysis of the connection between urban texture and energy consumption of buildings towards more sustainable buildings has become an important matter (Hofierka and Zlocha, 2012). Albeit conventional solar radiation models are limited in describing complex urban environments. They perform well to analyze 2D surfaces such as terrains and rooftops and can be applied in urban environments. However, they do not take vertical surfaces, like facades, into account. This circumstance has increased the interest in 3D solar radiation tools. (Morello and Ratti, 2009; Hofierka and Zlocha, 2012).

More importantly, several studies deal with approaches to overcome this limitation. While Ratti *et al.,* (2005) examined image processing techniques on DEMs to analyze the effects of urban texture on building energy consumption, their technique provides promising results.

However, Morello and Ratti (2009) pursued the analysis of complex urban environments based on the processing of DEMs and introduced the concept of calculating iso-solar surfaces. Therefore, iso-solar surfaces enable the calculation of different irradiation levels for 3D surfaces. Also, this technique can determine surfaces that receive a certain amount of solar radiation, nevertheless it is limited in representing the spatiotemporal distribution and therefore unsuited as solar radiation modelling tool. The better performance of computers in dealing with models with high vectorial complexity has led to new, vector based analysis tools. Albeit many GISs already provide 3D capabilities, but they are yet mostly limited to visualization.

Also, Hofierka and Zlocha (2012) examined a 3D solar radiation tool known as v.sun, developed for a GRASS GIS environment, using a vector-voxel approach. Although the urban features are represented as 3D vector objects defined by a set of vector surfaces (Hofierka and Zlocha, 2012). Likewise, the v.sun tool calculates solar radiation received at all urban surfaces, considering attenuation by shadowing effects of neighboring buildings. However, energy analysis tools coupled to a GIS offer an alternative to solely GIS-based tools. The 3D GIS techniques are used to build urban models, which then are analyzed with building energy analysis tools.

In the light of this, several studies propose that this data should be more than online text, it should be an interactive multimedia experience, including pictures, building details, 3D models, graphs, animations, etc. However, Deakin *et al.,* (2011, 2012, 2014) offer such a rendering of this material as part of an active and integrated institutional arrangement for low carbon buildings and the rest of this chapter shall report on the energy options appraisal and outcomes of this multi-media experience. Table 2 lists the solar potential modelling software reviewed for this study. Nevertheless, it seeks to provide a quick assessment of the software's characteristics.

Table 2: Summary of solar modelling software and its characteristics

Software	**Capabilities**	**Inputs**	**Strengths**	**Weaknesses**	**Availability**
SAGA-GIS *Potential Incoming Solar Radiation*	Calculation of direct + diffuse incoming solar radiation raster	DEM	Different models for atmospheric attenuation	Sky view factor must be given as input	Open source
GRASS GIS *r.sun module*	Calculation of direct, diffuse and reflected solar irradiation raster maps for given	DEM	Clear sky and overcast conditions	Advanced GIS knowledge required to process input parameters	Open source

	atmospheric conditions				
ArcGIS *AreaSolar Radiation*	Derives direct and diffuse incoming solar radiation from a raster surface	DEM	Highly accurate calculation for any given time and location	No calculation of reflected radiation	ArcGIS software license with SpatialAnalyst extension
SketchUp *ShadowAnalYst*	3D modelling Software	3D model	User friendly Operation	Shadow analysis only	Free Demo
GRASS GIS v.sun module	Solar radiation tool for 3D vector data, functionality as *r.sun* module	3D model	Potential to analyse complex urban environments	Not fully developed	Not publicly Available
Autodesk Ecotect	Complete environmental design software	3D model	Calculation of solar radiation, shadow analysis	Not designed to analyse whole urban extents	Not designed to analyse whole urban extents

2.4 Review of Energy Options Appraisal

The Energy Options Appraisal for Domestic Buildings, produced by Parity Projects in April 2008, sets out the “programme of work” for improving the energy efficiency and carbon emissions of the housing stock. It assesses the rates of energy consumption and levels of carbon emissions for the stock of housing within Hackbridge (as designated in the Masterplan) as part of the *surface to building volume ratio*. Brief attention is also given to profiling the resident community and referencing Census (2001) returns for the London Borough of Sutton. This analysis also details a number of energy efficiency measures that can be taken in order to turn the area under investigation into a low carbon zone (Deakin *et al.,* 2012a, 2012b).

While all very useful, the environmental profile advanced by Parity Projects is found wanting for the reason the Energy Options Appraisal is unclear as to whether the benefits generated from the forecast levels of energy consumption and carbon emissions will be spread equally amongst all residents. The explanation for this is simple: it is because, in order to clarify the distribution of benefits generated, it is first of all necessary for the institutional arrangement supporting the regeneration to first of all "baseline" the social-demographic composition of Hackbridge (Deakin *et al.,* 2012a, 2014). Then in the second instance, go on and draw upon the results of this analysis to assess whether this “innovative” environment has the capacity to carry the energy consumption and carbon emissions targets set for this redevelopment. This in turn will allow a judgement to be made as to whether the process of urban regeneration has the means to sustain any such energy efficient and low carbon (re)development of the suburb (Deakin *et al.,* 2014).

In seeking to fill these gaps in the existing Energy Options Appraisal, the case-study has sought to establish (Deakin *et al.,* 2012a, 2012b):

- whether the environmental profile generated is capable of not only being baselined in socio-demographic terms, but drawn upon as the means to evaluate if the benefits of the mass retrofit can be spread equally amongst the residents;
- or whether the costs emerging from the action are unevenly distributed across the structure of tenure within the housing market and if this undermines the claims made about the environmental sustainability of the action.

The assumption underlying the types of profiling exercises found in the existing Energy Options Appraisal suggests they do legitimate actions of this type and in turn, are effective in championing environmental sustainability. This is the assumption which the case-study seeks to investigate. Set within this emerging debate on the environmentally sustainability of urban regeneration, the specific objectives of this examination into the mass retrofit proposal are to (Deakin *et al.,* 2012a, 2012b):

- develop an environmental profile for the proposal that is based upon the regeneration boundary set out in the Masterplan, energy consumption and carbon emission data sourced from the Energy Options Appraisal;
- draw upon official statistical data currently available to analyse the social and demographic structure within the regeneration boundary and baseline the potential there is for the mass retrofit to transform Hackbridge into a sustainable suburb;
- use the outcomes of this social baseline analysis to review whether the energy-saving and carbon reduction measures can transform Sutton into a sustainable suburb and if this is achievable without burdening any residents with additional environmental cost.

Such an environmental profile is needed because currently neither the master plan nor Options Appraisal is sufficiently grounded in what this thesis refers to as an appropriate ‘‘area-based”, vis-a-vis, ‘‘in situ’’ analysis. The first and second objectives set for SURegen’s Involvement in the project offer the prospect of such an analysis. The third uses the data generated from this analysis to review the socio-demographic evidence such a baseline offers to evaluate the proposition made about the costs and benefits of the environmental profile. Together they will establish whether the project is not just well grounded, or sure-footed, but if the type of environmental sustainability it champions is both fair and equitable (Deakin *et al.*, 2012, 2014).

2.4.1 The Environmental Profile

The profiling exercise examined by London Borough of Sutton (2008b) sub-divides the stock of residences into six house types and is used to calculate both the energy savings and carbon emissions reductions generated from the range of retrofit options. Figure 9 shows the energy consumption and carbon emissions emanating from the collective housing stock within Hackbridge.

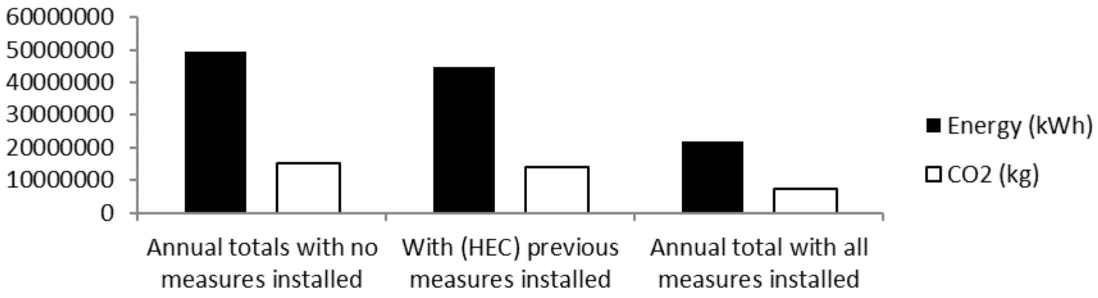


Figure 9: Potential Annual Energy and CO_2 Reductions (Deakin *et al.,* 2012a).

The paired columns to the right of Figure 9 illustrate the potential energy savings and CO_2 reductions assuming all the recommendations outlined within the account are taken up. The forecasted annual reductions if all measures are installed are predicted to result in 56.0% less energy consumption and 51.2% less CO_2 emissions from 1990 levels.

Tables 3 and 4 list the cost of the works needed for the retrofit to lower the levels of energy consumption and reduce carbon emissions. In some cases, alternatives are provided, such as in the proposed thickness of loft insulation. Both figures highlight these alternatives in grey.

Table 3: Cost of basic measures (Deakin *et al.,* 2012).

Measure	**Total Cost**
Loft Insulation - 300mm	£481,387
Loft Insulation - 400mm	£569,936
Draught Proofing	£414,132
Turn Heating from 18 to 17	£0
Boiler for One Hour Less Per Day (Controls Required)	£0
Energy Saving Light Bulbs	£165,599

Efficient Appliances	£599,922
TOTAL	**£1,661,040**
AVERAGE COST PER HOUSEHOD	**£691**

Table 3 lists basic measures assumed to be adopted by a high proportion of households without the need for professional assistance. These measures can be carried out immediately. The DIY percentage listed is the envisaged capability of residents to fulfil this requirement. The average cost of implementing such measures will be £691 per property.

Table 4: Cost of more complex measures (Deakin *et al.,* 2012a).

Measure	**Total Cost**
Secondary Glazing	£1,463,056
Solid Wall Insulation (Internal)	£6,328,197
Solid Wall Insulation (External)	£5,709,127
Under Floor Insulation	£1,281,581
Heat Exchange Ventilation	£1,556,069
Cavity Wall Insulation	£265,607
Double Glazing	£4,093,861
Triple Glazing	£5,018,332
Boiler Replacement	£973,792
Solar Water Heating (with Scaffolding Required)	£5,512,950
Solar Water Heating (no Scaffolding Required)	£4,608,990
Solar Voltaics	£4,946,103
TOTAL	**£25,802,16**

AVERAGE COST PER HOUSEHOLD	**£10,737**

Table 4 lists those measures which are mostly outside of the capability of households and instead require professional installation by qualified personnel. Implementing such measures will cost on average £10,737 per property.

Table 5: Average cost per household (Deakin *et al.,* 2012).

	Number of Households	**Total Cost**	**Average Cost Per Household**
Hackbridge Study Area	2403	£27,463,186	£11,429
Hackbridge Study Area: Owner Occupied (73%)	1754	£20,046,466	£11,429

Table 5 shows the total cost of implementing all the proposed measures, both DIY and professional, to be £27,463,186. With an average 73% owner occupation, the cost of implementing such measures within this sector is £20,046,466 or £11,429 per property within the study area (Deakin *et al.,* 2012, 2014).

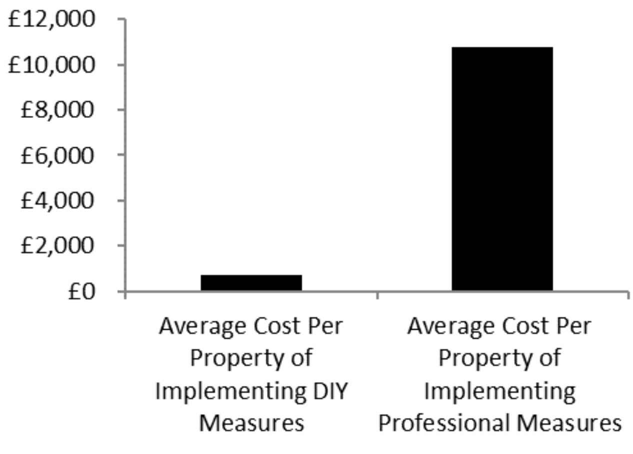


Figure 10: Average cost of DIY and professional measures (Deakin *et al.,* 2012).

In accordance with the terms of reference laid down for the retrofit, the costings are limited to those items of expenditure incurred by households in the owner-occupied and private-rented sector. Households in the social-rented sector are not factored into this costing and do not to form part of the retrofit proposal (Deakin *et al.,* 2012, 2014).

This profiling exercise goes on to identify 6 house types within the regeneration boundary: House Type B; House Type C; House Type F, House Type I, House Type J and House Type L. Variations within House Type F within the Energy Options Appraisal appear to have been based upon dwelling size rather than any significant difference in design so the "sub-types" within this group have been aggregated for Figure 11.

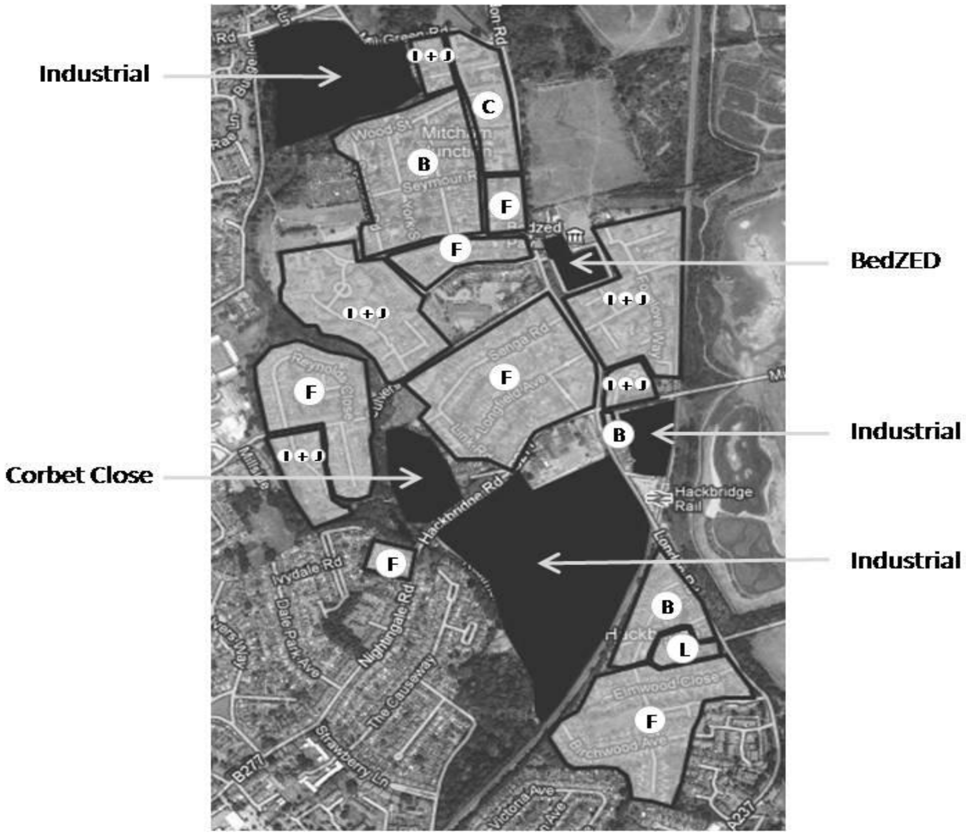


Figure 11: Hackbridge by House Type (Deakin *et al.,* 2012a)

Table 6: Hackbridge by House Type (Deakin *et al.,* 2012a).

House type	Construction Date	No. of Properties	%
L	Post 2001	57	2
I+J	1972-2000	872	37

F	1939-1959	913	38
C	1918-1938	121	5
B	Pre 1918	440	18
		2403	**100**

Here Hackbridge is identified as having a high proportion of housing stock built post 1972 (39%) and are likely to already have cavity insulation already installed. Similarly, those properties built pre-1939 (23%) are likely to have been built with solid single skin external walls and therefore are unable to receive cavity wall insulation. The Energy Options Appraisal suggests that remedial works targeted at the older housing stock will deliver the greatest improvements, whilst conceding that the necessary works are often more invasive and costly (Deakin *et al.,* 2012, 2014).

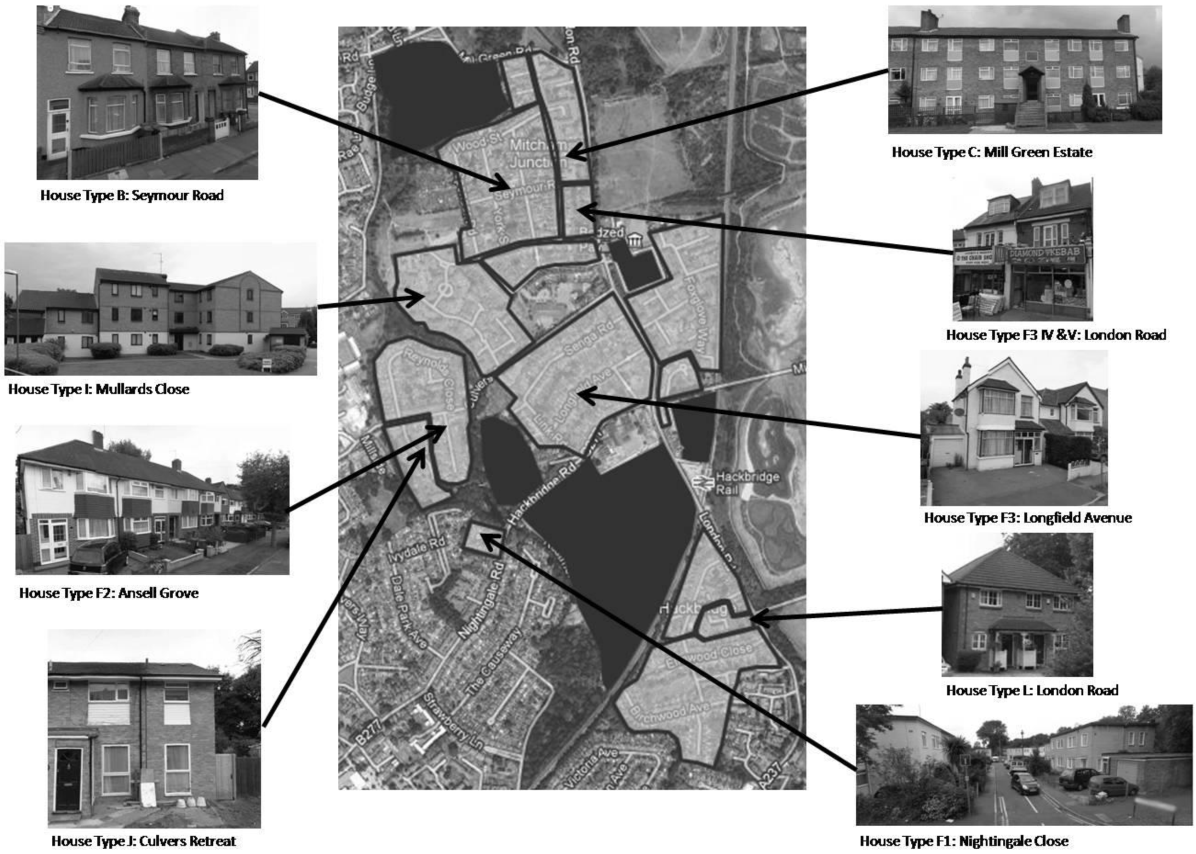


Figure 12: Hackbridge by house type location – images (Deakin *et al.,* 2012b).

2.4.2 Energy Consumption and CO_2 Emissions by House Type

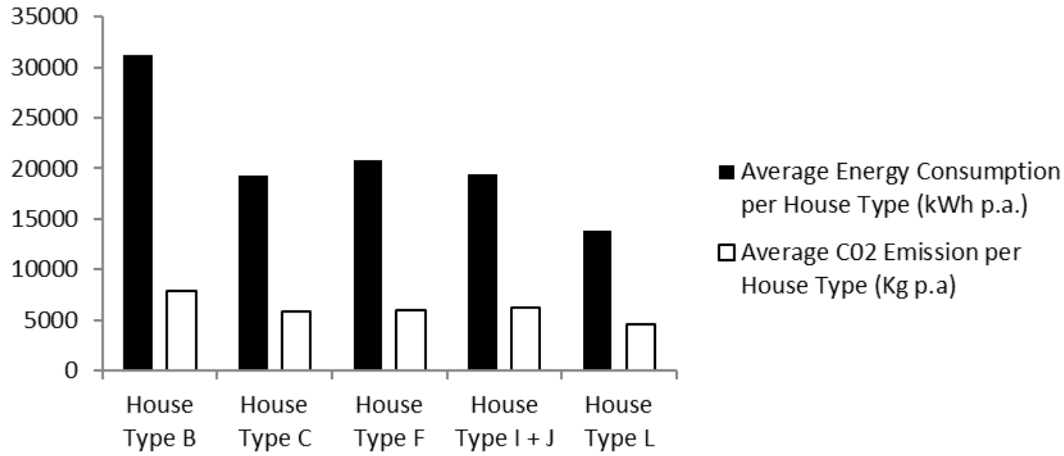
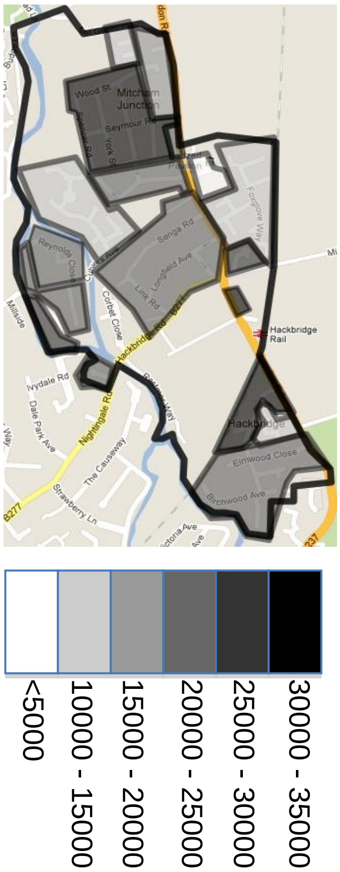


Figure 13: Average annual energy consumption and CO_2 emissions per house type (Deakin *et al.,* 2012a).

Deakin *et al.,* (2012) illustrated in Figure 13 that the older house types use more energy than the newer property types. Whilst energy consumption in Type B dwellings is highest, Type L homes consume the least energy. Similarly, it can be seen that the older housing stock (Type B, Type C and Type F) has a higher rate of CO_2 emission than the newer properties. This is demonstrated in Figure 14 by Type B (pre-1918) dwellings, which feature the highest rates of CO_2 emission and Type L (post 2001) which produce the lowest rates.

The following maps present a more detailed picture of energy consumption across the housing types. These have been collated using data from the Energy Options Appraisal to indicate energy consumption and consequent CO_2 emissions (Deakin *et al.,* 2014).



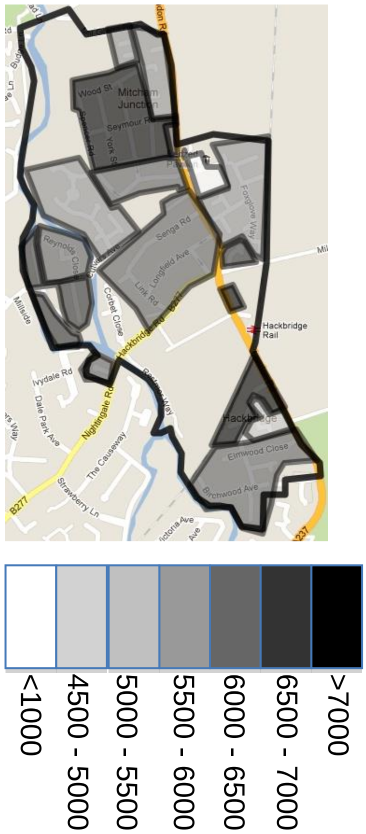


Figure 14: Energy consumption by house type (kWh); ***Figure 15:*** CO_2 emissions by house type. **Source:** Deakin *et al.,* (2012a, 2014).

Figures 14 and 15 are arranged according to the groups of similar housing stock identified in The Energy Options Appraisal then coded according to their consumption of energy and emissions of CO_2. Figure 14 shows pockets of high energy consumption (shown in dark grey) to the north and again in areas to the south. Similarly, pockets of low energy consumption can be seen across the map, in the north, where social deprivation is highest, and in the south where it is lowest (Deakin *et al.,* 2012a, 2014).

Figure 15 shows the CO_2 emissions detailed in the description. The method of calculating CO_2 emissions in the description was to multiply the energy consumption by conversion factors of 0.43 per kWh of electricity used and 0.18 per kWh of gas used. The highest emissions (7,500 - 8,000 kg CO_2 per annum) can be found in the north of the study area (Deakin *et al.,* 2014).

2.5 Social Baseline

The maps draw on data returns from the Census 2001 and EIMD 2007 [adapted from data from the Office for National Statistics licensed under the Open Government License v.1.0]. The base unit for census data release is the Output Area - a cluster of adjacent postcode units incorporating approximately 312 residents. The base unit for the EIMD 2007 is the Lower Super Output Area (LSOA): these are built from groups of 4–6 OAs and constrained by the wards used for the 2001 census outputs (Deakin *et al.,* 2012a, 2012b, 2014).

2.5.1 Classification of Social Groups

The standard measures of social deprivation in England are the English Indices of Deprivation (EIMD), produced by the Government and compiled in 2007. These provide a ranking system whereby small geographical units, known as Lower Super Output Areas (LSOAs), are rated against 37 indicators and then ranked in relation to one another. LSOAs are home to approximately 1,500 people: there are a total of 32,482 LSOAs in England. As the LSOAs are ranked comparatively, rank 1 indicates the most deprived LSOA in England and rank 32,482 the least (Deakin *et al.,* 2012a, 2014).

The outline for Hackbridge has been prepared using the Google “My Maps” function (Figure 16). A second map has subsequently been prepared showing the outlines of the Lower Super Output Areas spanning Hackbridge (identified using ONS Boundary Viewer and as shown in Figure 17). The map of the study area has been superimposed upon the map of the LSOAs to confirm appropriate coverage (Figure 18).

Figure 16

Figure 17

Figure 18

The Lower Super Output Areas within the Hackbridge study area (outlined in black), have been numbered from one to five and are shown in Figure 19.

Figure 19: Hackbridge sub-sections by number (Deakin *et al.,* 2012a).

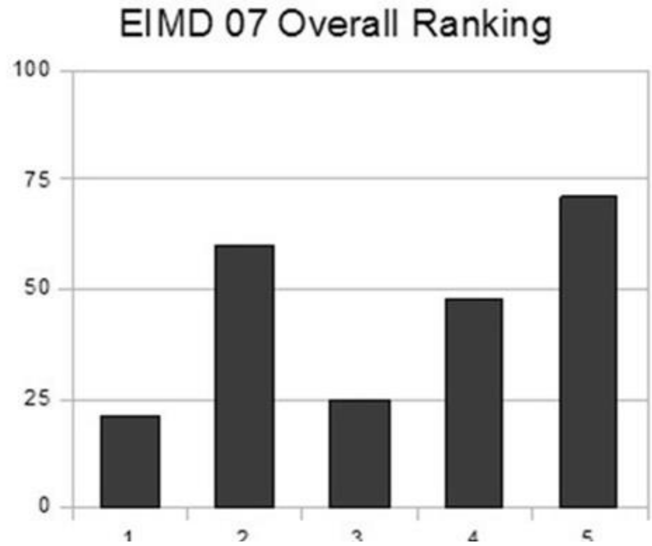


Figure 20: The overall deprivation ranking - where 100% is the **least** deprived in England (Deakin *et al.,* 2015).

As Deakin *et al.,* (2015) illustrates in Figure 20, Hackbridge is home to a large population who rank in the 50% *least* deprived in England. For the purposes of this description, each LSOA has been labelled from 1 to 5: areas within the 50% least deprived in England are labelled 2 and 5. However, Hackbridge is also home to a population amongst the 25% most deprived in England - in the area labelled 1 - with an overall ranking of 6,768 (where 1 is the most deprived and 32,482 is the least). A second LSOA is ranked at the 25% mark; this is the small area labelled 3. However, as Figure 20 indicates, it is suggested that care must be taken when interpreting data returns for Area 3 as only half of the surface area is included within the Hackbridge Study Area (outlined in black). In total, three LSOAs, with an approximate combined population of 4,500, are home to people within the 50% most deprived in England (Deakin *et al.,* 2012a, 2015).

In order to understand these figures, it is important to consider each of the areas covered by the Indices in turn. The Indices of Deprivation (2007) were calculated across 7 domains: Income; Employment; Health and Disability; Education, Skills and Training; Barriers to Housing and Services; Living Environment and Crime.

2.5.2 Deprivation across the Domains

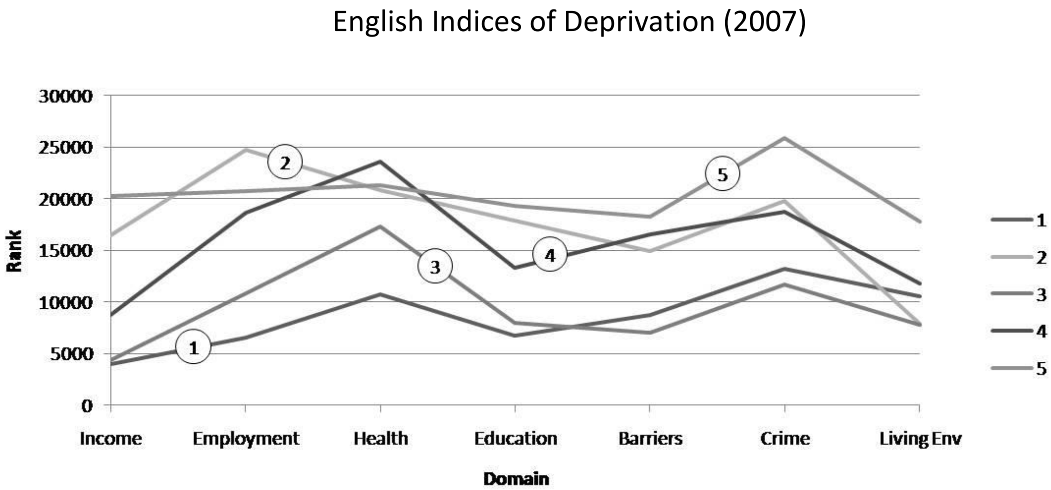


Figure 21: Multiple deprivation ranking - *where a ranking of 32,482 is the **least** deprived in England* (Deakin *et al.,* 2014).

Figure 21 demonstrates deprivation ranking in the five LSOAs within the study area. These are labelled 1 – 5 as shown in Figure 20. Findings from each domain are as follows (Deakin *et al.,* 2012a, 2014):

i. the Income Domain is designed to identify sections of the population experiencing income deprivation, with particular attention to those reliant upon various means-tested benefits. None of the LSOAs within the case study area fall within the 10% most income-deprived in England; however, two of Hackbridge's LSOAs are ranked within the 20% most deprived (Areas 1 and 3) and one is ranked within the 30% most deprived (Area 4). The actual score given to each LSOA represents the area's income deprivation rate. This means that in Area 1, 32% of residents can be described as income-deprived. To the west, in Area 3, 30% of residents can be described as income deprived. By contrast, in Area 5 to the south of Hackbridge station, only 9% of residents are income-deprived.

ii. the EIMD 2007 conceptualises employment deprivation as “the involuntary exclusion of the working-age population from the world of work”. The highest rate of employment deprivation in Hackbridge is 15%, seen in Area 1. This is in the 30% most deprived areas in England. By contrast, the area immediately south of this LSOA (Area 2) has an employment deprivation rate of 5%; amongst the 20% least deprived in England.

iii. the Health and Disability domain measures morbidity, disability and premature mortality in each given area. Area 1 is the most health-deprived, ranking within the 33% most deprived in England. Area 4 ranks within the 28% least health-deprived in England.

iv. the Barriers to Housing and Services domain is calculated over two sub-domains: geographical barriers and so-called “wider” barriers, which includes issues relating to the affordability of local housing. Area 3 is the most deprived within the study area and is within the 22% most deprived in England.

v. the Education, Skills and Training deprivation domain measures deprivation in educational attainment amongst children, young people and the working age population. Area 1 ranks at 21% most deprived in England; its high ranking owing to the low rate of young people entering Higher Education each year. Area 3 ranks at 25%; again, largely due to its low HE progression rate.

vi. the Crime domain measures the rate of recorded crime for 4 major volume crime types: burglary, theft, criminal damage and violence. The EIMD 2007 proposes that this domain represents “the risk of personal and material victimisation at a small area level”. In this domain, Area 3 is ranked within the 36% most deprived and Area 1 within the 41% most crime deprived. Area 5 ranks in the 20% least deprived in England, in terms of crime.

vii. the Living Environment domain is, in fact, calculated over two sub-domains: indoors and outdoors. Indoors, the domain identifies deprivation by measuring housing in poor condition and houses without central heating. Outdoors, air quality is measured across several parameters and the number of road traffic accidents involving injury to pedestrians and cyclists is incorporated. In terms of Living Environment deprivation, both Areas, 2 & 3 rank within the 24% most deprived in England.

From these measures, Deakin *et al.,* (2015) also suggests that a pattern is evident in the area's overall EIMD rankings: two pockets of relative deprivation to the north and west of Hackbridge, with relative prosperity to the south of the study area. These measures of deprivation are, in turn, compounded by the health, housing, education, crime and living environment rankings.

2.5.3 Structure of Tenure within the Housing Market

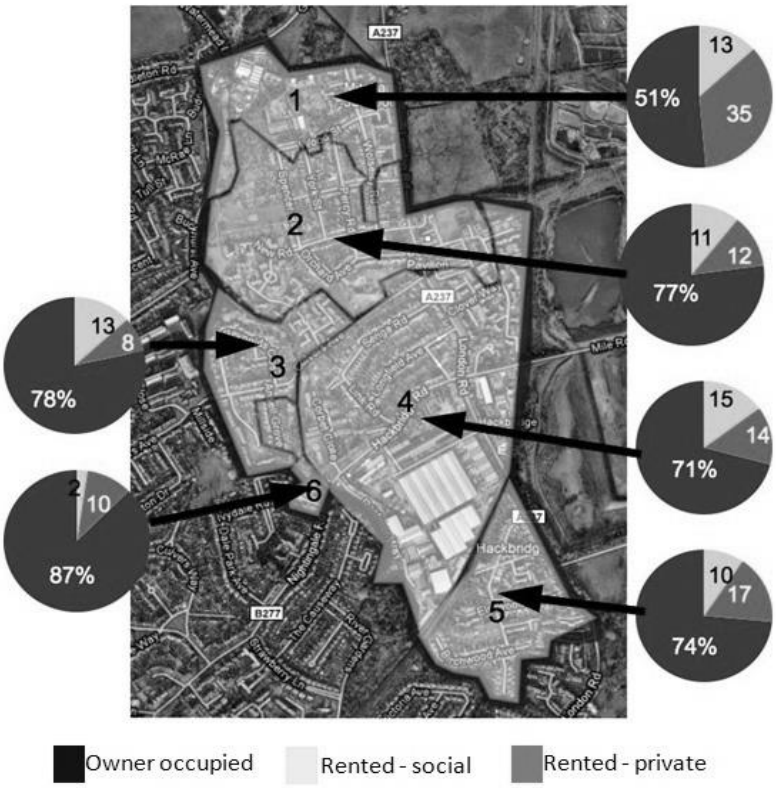


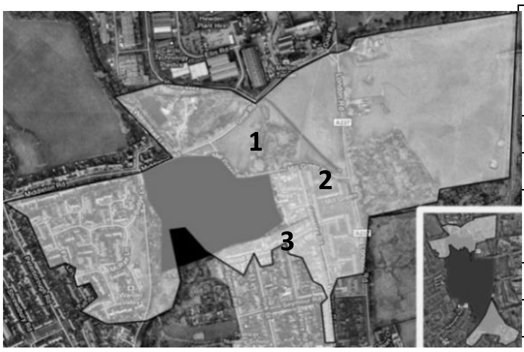
Figure 22: Housing Tenure in Hackbridge (Deakin *et al.,* 2012b).

According to Deakin *et al.,* (2012a), Figure 22 demonstrates the structure of housing tenure within the study area. As the data returns in this instance were at Output Area level (the smallest unit of spatial analysis) it is possible to include a 6th area: a section of 127 households. The data returns (at Output Area level) have been shown within the Lower Super Output Areas (numbered 1 – 5) for the purposes of clarity. As the Figure shows, owner-occupation in Hackbridge is above the English average of 68.72% in all but one area. Social rented accommodation is below the average of 19.26% in all areas, and privately rented accommodation exceeds the average figure of 8.80% in all areas but one (Deakin *et al.,* 2012a, 2015).

2.6 Area-Based Analysis

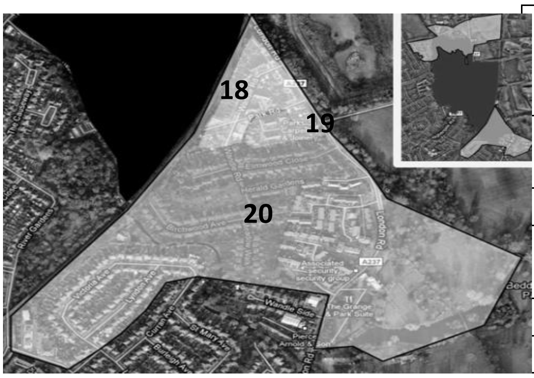
The following relates the socio-demographic data to the environmental profile. This is achieved by way of an area-based analysis, linking levels of energy consumption and carbon emissions to the structure of tenure and the connection this has to the housing market. As an area-based analysis, this assessment of consumption and emissions by structure of tenure draws upon data profiled from LSOA’s 1 and 5. The reasons for focusing attention on these areas are (Deakin *et al.,* 2012a, 2012b, 2014):

i. LSOAs 1 and 5 provide measures of the most and least deprived areas within the urban regeneration boundary. Here, Area 1 is the most deprived with a ranking within the 21% most deprived areas in England, whereas Area 5 has a much lower ranking within the 30% least deprived;
ii. while roughly similar in terms of building type, age, and levels of consumption and emissions, the social-rented sector is prevalent in Area 1, whereas in Area 5 the owner-occupied and private-rented sector are the main sectors of the housing market;
iii. such an area-based analysis provides evidence to suggest which type of tenure consumes the least or most amount of energy and illustrates the relationship which this, in turn, has to the levels of emissions within the housing market.



Type	Age	HA	Average Energy Consumption (kWh p.a.)	Average CO^2 Consumption (kg p.a.)	Tenure (%)		
					Owner Occupied	Private Rented	Social Rented
I	1990s	1	13631	5861	80	12	8
C	1930s	2	19248	5841	29	15	56
B	1890-1920	3	31204	7807	80	12	8
Total			64083	19509			
Average			21361	6503			

Figure 23: Profile of housing, energy consumption and tenure within the most deprived area of Hackbridge (LSOA 1) (Deakin *et al.,* 2012a).



Type	Age	HA	Average Energy Consumption (kWh p.a.)	Average CO^2 Consumption (kg p.a.)	Tenure (%)		
					Owner Occupied	Private Rented	Social Rented
B	1896-1913	18	31204	7807	87	10	3
L	1990s	19	13791	4618	87	10	3
F	Late 1930s	20	23626	6420	85	3	12
Total			68621	18845			
Average			22874	6282			

Figure 24: Profile of housing, energy consumption and tenure within the least deprived area of Hackbridge (LSOA 5) (Deakin *et al.,* 2012a).

The description for Figures 23 and 24 are stated below:

i. "Type" refers to the housing model applied in the Energy Options Appraisal [Figure 12: Hackbridge by House Type]

ii. "Age" refers to the approximate year of build, as designated in the Energy Options Appraisal

iii. "HA" refers to the designated localities of similar housing stock in the Hackbridge Study Area, as detailed in the Energy Options Appraisal. Twenty areas of similar housing stock were identified and are used here to show the different housing stock within the lowest-ranking Lower Super Output Area (EIMD 2007) and the highest-ranking LSOA.

iv. Energy and CO2 data has been taken from the Energy Options Appraisal

v. “Tenure” data has been taken from the Census 2001 at Output Area level. The HA (areas of similar housing) are smaller than Output Areas therefore exact counts for each area of housing cannot be provided. The percentages shown represent a best-fit analysis at Output Area level.

Deakin *et al.,* (2012a, 2012b) suggests that Figure 23 shows the relationship between the building type and age of construction by Housing Area (HA) 1, 2 and 3, levels of energy consumption and carbon emissions for the same, split across the structure of tenure. HA02 is predominantly social-rented in terms of tenure type and has an energy consumption rate of 19,248 (kWh/p.a.), 2,113 (kWh p.a.) or 11% below the overall average for the owner-occupied, private-rented and social rented sectors of the housing market in LSOA 1. Deakin *et al.,* (2012a) recommends that Figure 24 goes on to demonstrate the same relationships for HAs 18, 19 and 20 in LSOA 5. Here the structure of tenure is predominantly owner-occupied and private-rented and the average energy consumption is 21,926 (Kwh/p.a.), 565 (Kwh/p.a.), or 3% higher than the average for LSOA 1.

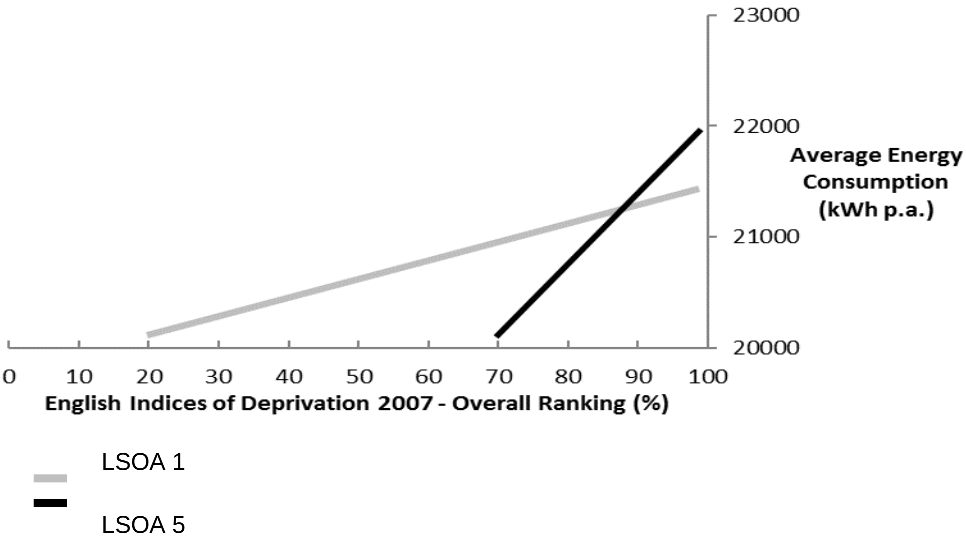


Figure 25: The relationship between deprivation and energy consumption in LSOA 1 and LSOA 5 (Deakin *et al.,* 2015).

In addition, Deakin and his team suggests that the diagram above clarifies deprivation and energy consumption values for LSOA 1 and LSOA 5 only.

Nevertheless, it is not intended to suggest a linear relationship between deprivation and energy consumption.

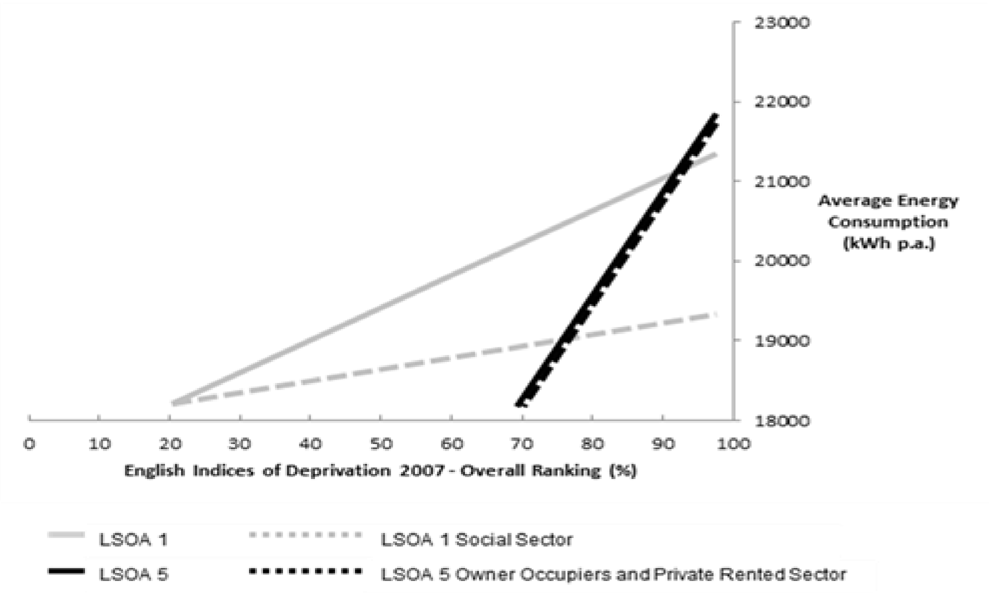


Figure 26: The relationship between deprivation and energy consumption in the social and owner occupier (including private rental) sectors. (Deakin *et al.,* 2015).

Similarly, Deakin *et al.,* (2015) explains in Figure 25 that LSOA 1 (HAs 1, 2 and 3), located within the 21% *most* deprived in England, has the lowest levels of energy consumption and LSOA 5, situated within the 29% *least* deprived in England (HAs 18,19 and 20) the highest. It is suggested that Figure 26 clarifies the levels of energy consumption within the 21% most and 29% least deprived LSOAs (1 and 5 respectively) and shows how they are split across the social-rented, owner-occupied and private rented sectors. Within the social-rented sector of LSOA 1 (HA 2), it illustrates the average level of consumption to be 19,248, whereas in LSOA 5 (HA 18, 19 and 20) this is shown to be 21,926 or 14% higher for the owner occupied and private rented tenures.

In the light of this, Deakin *et al.,* (2015) suggested that as the CO_2 emission levels are similar for both LSOAs 1 and 5 (HAs 1, 2, 3 and 18, 19 and 20), they are not seen as warranting such an area-based analysis.

2.7 Summary

The case study which has been decided to demonstrate the strategic value of mass retrofits in the housing sector is that known as the Hackbridge project. It has been picked because this project offers a particularly decent example of the reaction made by the London Borough of Sutton to move past the state-of-the-art and underpin their vision of urban regeneration with a Master-plan. In particular, inside a Master-plan that is not just capable of supporting a program of renewal, however which also enables the redevelopment of properties with a current utilization, by means of adaptation and renovation. That is to say, by way of and through a mass retrofit, intended to lower rates of energy utilization and reduce rates of carbon emissions in accordance with the targets which the UK Government have laid down for the housing sector under the 2008 Climate Change Act.

The socio-demographic baseline of the study area has been compiled using data from the English Indices of Deprivation, 2007 and 2001 Census. The results of this investigation have been aggregated at Lower Super Output Area level and the overall ranking of these areas shows a mix of relatively deprived and prosperous residents. In expanding this social-demographic baseline to also include data on building type, age, levels of consumption and emissions across the structure of tenure within the housing market, it has been possible for the analysis to cross reference the rate of energy consumption and level of carbon emissions within these areas to the structure of tenure.

Also, this finding demonstrates the value of grounding urban morphology not so much in technical matters, but in the social, environmental and economic relationships whose forces do much to set the surface-to-volumes and passive-to-non-passive area measures in the specific forms (i.e. neighborhoods of district centers) drawn attention to by (Ratti, *et al*., 2005) and subjected to a detailed baseline analysis in this investigation. For as a baseline the analysis serves to enrich the content of such measures by drawing attention to the design and construction of house types, structure of tenure and occupational behaviors by the user groups associated with the context-specific form the retrofit proposal takes on. That context-specific form which the retrofit proposal takes on and that which in turn makes up the content of the transformation. That content which otherwise would fail be captured in any such baseline analysis, go unnoticed and be left out of the transformation.

These observations be summarized as follows:

- housing built pre-1918 on average consumes 56% more energy and emits 41% more CO_2 than houses built post-2001;
- the older housing stock is the worst performer in terms of energy efficiency and is the most costly to improve;
- within the regeneration boundary this type of housing makes up less than 20% of the housing stock. Nearly 40% of the housing stock having been built post-1970 and is already benefitting from many of the measures proposed to save energy and reduce carbon emissions;
- almost one third of Hackbridge residents live in areas which rank within the top 15% most income-deprived in England, renting their homes from the Local Authority, Registered Social Landlords, Housing Associations or the private-rented sector. These homes in the social-rented sector have been shown to consume less energy and to emit less CO_2 than other housing type of a similar age in Hackbridge.

The mass retrofit related to this study may be seen as being divisive in terms of not just in terms of the volume and area, but extent, breath and depth of the transformation which it lays out as measures for improving the energy efficiency and carbon footprint of the housing market. For under this exploration, it can be consequently realized that renewables are the major components of the mass retrofit study as it supports to decrease levels of energy consumption and carbon emission, vis-à-vis to create energy efficient-low carbon zones as an implementation in the improvements of sustainable suburbs that not only attacks global warming, however, prevents climate change. Besides, this thesis shall argue that in adopting renewables as the key component of the study, it is possible to open-up this landscape of energy efficient-low carbon zones, sustainable suburbs and situate it within the ongoing debate over global warming and climate change. It argues: the key to this lies in developing a renewable-based key component model of urban morphology. That is a renewable based model of urban morphology founded on a procedural modelling approach, able to contextualize this as the analytical framework of mass retrofit proposals and in terms of the energy consumption, carbon emissions of the building, that make up this environment and users which occupy them as the energy efficient low-carbon zones of sustainable suburbs.

By means of this lies a methodological encounter that stands a major significant and ways of progressing a key-renewable-based model of urban morphology and establishing a much-detailed procedural modelling approach. It allows for a component based analysis of energy consumption and carbon emission by source, and therefore single out the contribution solar as a renewable energy makes to efficiency of low carbon zones: this has previously not been possible and this is shown in the fact the options appraisal cannot account for the contribution solar makes to the overall savings/ reductions. So, we do not know the real contribution it makes. The morphological analysis allows for this and what follows shall develop the methodology to conduct such an analysis. For this reason, the procedural modelling adopted shall be examined, vis-à-vis to enhance an LoD 1 level of analysis into LoD 2 that apprehends the roof structures of Hackbridge suburb. Also, it shall then lay emphasis on the improvement of this procedural modelling approach as the methodical context adequately thorough to apprehend the surface, shape and form required for this modelling approach of urban morphology, vis-à-vis to produce the data needed and apprehend the information mandatory to analyze the levels of energy consumption and carbon emission of this Hackbridge suburb. More importantly, as a standard method which to evaluate the possible savings of the mass retrofit, in terms of the savings attained from this achievement and in turn will grant this thesis to appraise the significance renewables integrated into the mass retrofit proposal, energy consumption, carbon emissions that brings about as an energy efficient low-carbon zones.

Chapter Three

3.0 Methodology

3.1 Introduction

As an exercise in procedural approach of 3-D city modelling, this chapter clearly sets out the research methodology of urban morphology that builds upon the previous studies undertaken to examine the potential of mass retrofits by representing roof structures as a principal component of energy consumption and carbon emissions in buildings and solar panel installations as turnkey elements in the drive towards the development of energy efficient-low carbon zones.

3.2 Research Approach

This section offers the research approach adopted to study the urban morphology of mass retrofit proposals and capture the potential contribution solar panels installed onto the roof of buildings make to levels of energy consumption and rates of carbon emission. In studying the urban morphology of mass retrofit proposals, the methodology adopts a procedural modelling approach to the research. This modelling approach sets out the building footprints of the mass retrofit proposal and supplements this data with the height information needed to calculate the amount of renewable energy it is possible to generate from the solar panels installed on the roof structures. It strategically focused on the development of procedural modelling approach as the analytical framework sufficiently detailed to capture the surface, shape and form needed for this 3D modelling of urban morphology to generate the data needed and capture the information required, to diagnose the levels of energy consumption and carbon emission as a baseline. In particular, as a baseline from which to assess the potential savings of the mass retrofit in terms of the savings that are gained from any such action. This in turn allowed the thesis to evaluate the significance renewables take in the mass retrofit proposal, energy consumption, carbon emissions, it in turn generates as an energy efficient-low carbon zone. As an energy, efficient-low carbon zone users' inhabitant as a sustainable suburb that tackles global warming and which combats climate change as part of an adaptation strategy.

As previous morphological studies of mass retrofit proposals have only been developed to Level of Detail 1 (LoD 1), they have been unable to capture the potential contribution solar panels installed into building make to levels of energy consumption and rates of carbon emission, this 3-D City model. Consequently, the modelling approach adopted to support this research methodology augment this and supplement previous LoD 1 into LoD 2. This allows the urban morphology of the mass retrofit forming the subject of this study to render roof structures a principal component of energy consumption and the carbon emission, by supplementing building footprint data with height information. In particular, with that data and information needed to calculate the amount of renewable energy, which it is possible to generate from the solar panels installed onto roof structures and key drivers in the development of energy efficient-low carbon zones as sustainable suburbs.

This level of detail clearly proves the degree to which the urban morphology of mass retrofit proposals is green. It offers the renewables of this key-component-based urban morphology and procedural modelling this is founded on. Also, it allows this approach to offer technical components of the renewables, the context of the application in terms of and from, the buildings and their integration into the context of the mass retrofit under examination. In particular, based on renewable energies, vis-a-vis solar power as alternatives to fossil fuels and contribution this alternative source of energy makes to the development of energy efficient-low carbon zones as sustainable suburbs, able to tackle global warming and combat climate change as part of an adaptation strategy.

3.3 Procedural Modelling Approach and Justification

Procedural modeling is an umbrella term for several techniques in computer graphics to create 3D models and textures from sets of rules. L-Systems, fractals, and generative modelling are procedural modeling techniques since they apply algorithms for producing scenes. The set of rules may either be embedded into the algorithm, configurable by parameters, or the set of rules is separate from the evaluation engine (Ganster and Klein, 2007; Derzapf *et al.,* 2011; Smelik *et al.,* 2014).

Although all modeling techniques on a computer require algorithms to manage and store data at some point, procedural modeling focuses on creating a model from a rule set, or enhancing models automatically. Procedural modeling is often applied when it would be too cumbersome to create a 3D model using generic 3D modelers, or when more specialized tools are required. This often justifies the case for modelling specific types of models (Derzapf *et al.,* 2011; Muller *et al.,* 2006; Ganster and Klein, 2007).

The justification for this method unfolds that it would be too cumbersome to generate a 3-D city model for Hackbridge suburb, however, objects to combine modelling methods applied in procedural modeling by adopting existing approaches to model specific types of models for this study and/ or applying generic procedural modeling approaches.

3.3.1 Procedural Modelling Basis in Existing Study

The concept of procedural modeling approach for multiple representations on different scales is well known from both cartographic applications as well as 3D city modeling. For example, CityGML, an open standard for the storage of 3D city models based on GML, provides five different Levels of Detail (Kolbe 2008). The LoD concept in these application areas using procedural modelling relies on the independent storage of individual geometric models on each level of detail. As the dependency between the individual levels is not explicitly represented, inconsistency may arise easily. Nevertheless, for geographic applications the concept of independent LoD representations is well suited since GIS applications are relying on rather static data sets, which are rarely subject to modifications. For the highly dynamic development stage of mass retrofitting projects like Hackbridge venture, a procedural modelling approach is required. To realize this, definition of explicit dependencies is proposed between the different levels of detail during the creation of the multi-scale model. The creation is intended to be performed top-down, i.e. from coarser levels to the finer one, thus reflecting the typical planning procedure. This top-down approach for defining and managing multi-scale geometry is contrasting with the well-known procedural modelling methods used in 3D city modeling applications, which implement a bottom-up approach usually known as generalization (Forberg 2006; Meng & Forberg 2007). This can be explained by the fact that in adopting procedural modelling approach for 3D city modeling, maps are created by subsequently abstracting real-world objects, whereas in civil engineering the workflow starts at an abstract level, with the design becoming more and more concrete as planning evolves.

Also, the technique in this study relates to research in sketch-based modeling, example based modeling, and/ or general procedural modeling approach. Procedural modelling attempts to make 3D modeling as direct and intuitive as drawing (Olsen *et al.,* 2009). However, recovering a 3D model from a 2D drawing is fundamentally ill-posed because strokes do not provide depth information. Early approaches made this problem well posed by assuming that the lines in the drawing obey specific geometric constraints in 3D, or by using a well-defined set of gestures to specify one of a set of primitive shapes (Zeleznik *et al.,* 1996). For smooth shapes, the lines can be assumed to denote contours and silhouettes (Igarashi *et al.,* 1999), while for polyhedrons geometric relationships such as parallelism, orthogonality and planarity can be detected and imposed (Lipson and Shpitalni, 1996), or even learned from line-renderings of 3D models (Lipson and Shpitalni, 2000). Unfortunately, such assumptions only hold for a limited family of shapes. Recent methods allow the creation of complex free form shapes by exploiting geometric constraints present in professional design drawings, such as polyhedral scaffolds (Schmidt *et al.,* 2009) and cross-section lines (Xu *et al.,* 2014). Interactive systems also rely on axis-aligned planes and other transient surfaces such as 3D canvases to support 3D strokes (Bae *et al.,* 2008; Zheng *et al.,* 2016). Since all the above methods derive constraints from the drawn lines using procedural modelling, they require relatively accurate drawings as input. In addition, these methods only reconstruct what is drawn, which means that users must draw very detailed sketches to obtain detailed 3D models. In contrast, this study relies on procedural grammars as a strong prior to regularize inaccurate and unclear sketches as well as to suggest intricate details from a handful of lines using procedural modelling concept.

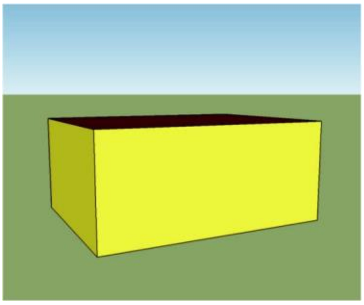
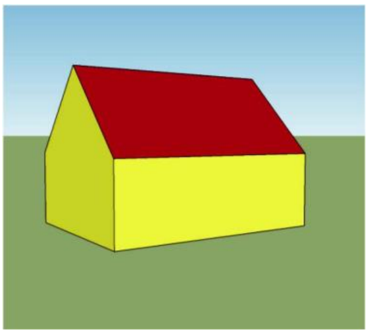
Consequently, procedural modeling offers an effective way of generating complex, parameterized 3D models (Wonka *et al.,* 2003; Muller *et al.,* 2006; Smelik *et al.,* 2014). Among procedural models, grammar based models are commonly used in urban modeling and vegetation. Procedural systems can quickly generate many 3D models with wide variation by either changing the grammar or by varying its attributes. However, creating a grammar requires programming expertise and domain knowledge to be able to write compact rules, and setting the parameters of a grammar is non-trivial because of the intricate relationship between the procedural parameters and the output. To address this issue, Lipp *et al.,* (2008) introduce a visual editor akin to standard 3D modeling software, allowing direct editing of architectural models by selecting and dragging procedural components. Several sketch-based systems have also been proposed for specific domains, such as trees (Ijiri *et al.,* 2006), terrains (Smelik *et al.,* 2010), and roads (Applegate *et al.,* 2012; Chen *et al.,* 2008a). However, these methods rely on application dependent heuristics procedural modelling rather than on a generic algorithm in procedural modelling approach utilized in this study. Inverse procedural modeling estimates the parameters of procedural models by minimizing an objective function defined by the user input and the parameter values.

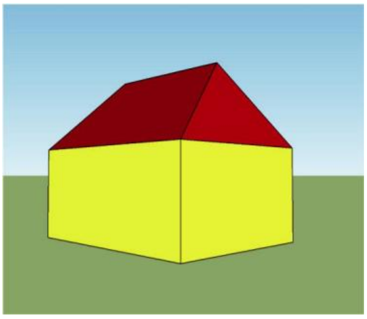
Research studies by Talton *et al.,* (2011); Vanegas *et al.,* (2012); Stava *et al.,* (2014) and Ritchie *et al.,* (2015) offers the most promising solutions to explore the large parameter space and find near-optimal parameter values for procedural modelling. However, these iterative sampling algorithms require many steps to converge, preventing their use in an interactive context. Recently, Emilien *et al.,* (2015) learned localized procedural models from examples and reused them for sketching virtual worlds. However, their approach is suited for stochastic models and fails to represent structure and its repetition. This study exploit recent advances in modelling to perform procedural modeling for Hackbridge venture at runtime without the cost of iterative optimization. This approach is inspired by recent work of Deakin *et al.,* (2011; 2012; 2014; 2015).

3.4 Modelling Roofs Structures

Retrofitting the existing block model in Hackbridge districts requires the modelling of roof structures for the buildings. However, recent studies suggest that the Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany (AdV) offers modelling examples to develop 3D city models in LoD 2. Also, these examples are intended as standards to achieve a consistent dataset and enable software aided modelling for LoD 2 city models within Hackbridge suburb.

Table 7: Modelling patterns for 3D city models in LoD 2 (AdV, 2013).

Roof shape	Description	Modelling example (LoD2)
Flat roof	Flat roofs are roofs with no pitch, or a pitch of less than 10°.	 Flat roof
Gable roof	Gable roofs consist of two opposite tilted roof surfaces, which meet at the roof ridge.	 Gable roof

Hip roof	Hip roofs consist of four sides, which all slope downwards to the walls. The ridge has a continuous height and the roof sides have the same pitch.	 Hip roof

3.4.1 Hackbridge Roof Structures

The characteristic of a roof is strongly influenced by additional roof structures like chimneys and dormers. A visual assessment of satellite images represented in figure 27 uncovers that besides chimneys, many roofs have shed and eyebrow dormers.

(a). (b)

Figure 27: Satellite images of characteristic eyebrow dormers (left) and shed dormers (right) in Hackbridge (Bing Maps, 2015).

The AdV regulations specified that only distinctive objects should be modelled. Despite the fact that this model will be used for a solar potential analysis, structures are defined distinctive if they cast shadows and therefore influence the solar radiation estimates.

3.4.2 Roof Geometry

For Hackbridge suburb, the pitch of the roof simply represents the steepness of the roof and can be calculated knowing a buildings width and the height of the roof. It is defined as the vertical rise divided by the horizontal span as shown in figure 28.

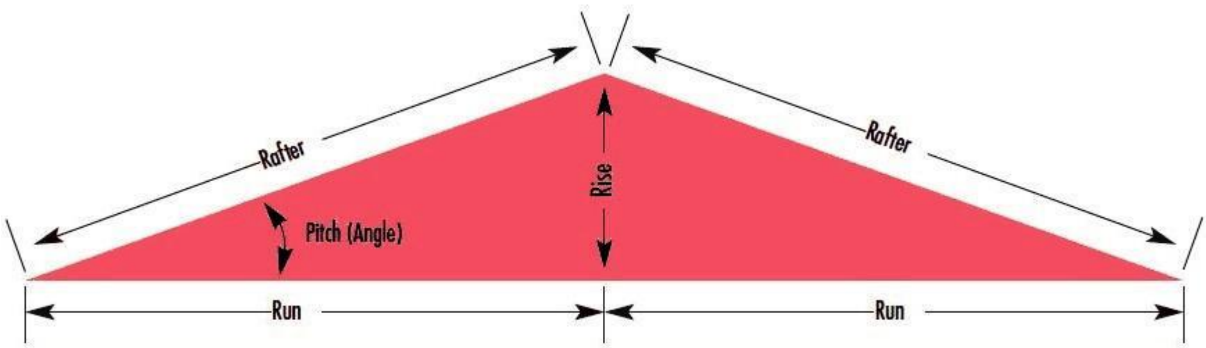


Figure 28: Visualisation of roof geometry terms (Adapted from Matchatile, 2015).

In this instance, there are two ways to indicate the roof pitch. The first one uses imperial units and gives the pitch as ratio of however many inches the roof rises for a 12-inch run. The second one uses trigonometry to determine the pitch angle in degrees. To calculate the pitch in degrees, the rise is divided by the run. The result, the tangent, must be inverted to get the angle in degrees (formula 1).

Angle = Arc tan (Rise/Run). (1)

The pitches determined for this thesis are given in degrees.

3.4.3 Evaluation of Level of Detail

Level of Detail (LoD) is an important concept in 3D city modelling of Hackbridge suburb which define the degree of abstraction of real-world objects, primarily designated to examine an optimum amount of details of real-world objects for this present study needs, and computational and economical aspects. The CityGML standard defines the proposed use and the main characteristics of the LoDs as following:

- LOD 0 – regional, landscape (2.5D Digital Terrain Model)
- LOD 1 – city, region (block model)
- LOD 2 – city districts, projects (differentiated roof structure)
- LOD 3 – architectural models (outside), landmarks (detailed wall and roof structures)
- LOD 4 – architectural models (interior structures)

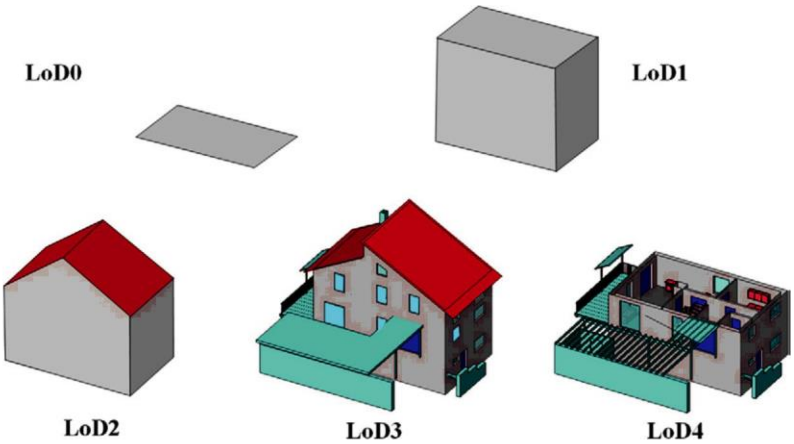


Figure 29: Level of detail for residential buildings (Open Geospatial Consortium, 2006).

This study focused on buildings in LoD 2 that has differentiated roof structures and thematically differentiated boundary surfaces which is in turn most suitable for Hackbridge suburbs. Practically, the relation between LoDs could be illustrated in Figure 30.

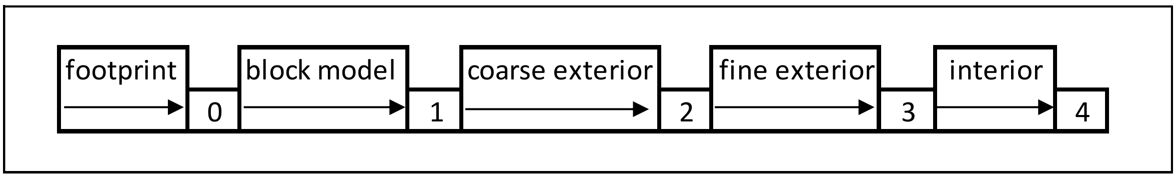


Figure 30: Practical connections between the Level of Details.

3.4.4 Morphological Model

This model begins by setting out the pretext to the interest in climate change and application of the morphologic models. Here particular attention is drawn to the mass retrofitting of an energy efficient-low carbon zone as a sustainable suburb both by way of advancing a key-renewable-based model of urban morphology, vis-à-vis to supplement an LoD 1 level of analysis into a LoD 2 that captures the roof structures as integral components of urban morphology and integrating them into the thermography of the power, heating and lighting systems of the structures of those housing an energy efficient-low carbon zone.

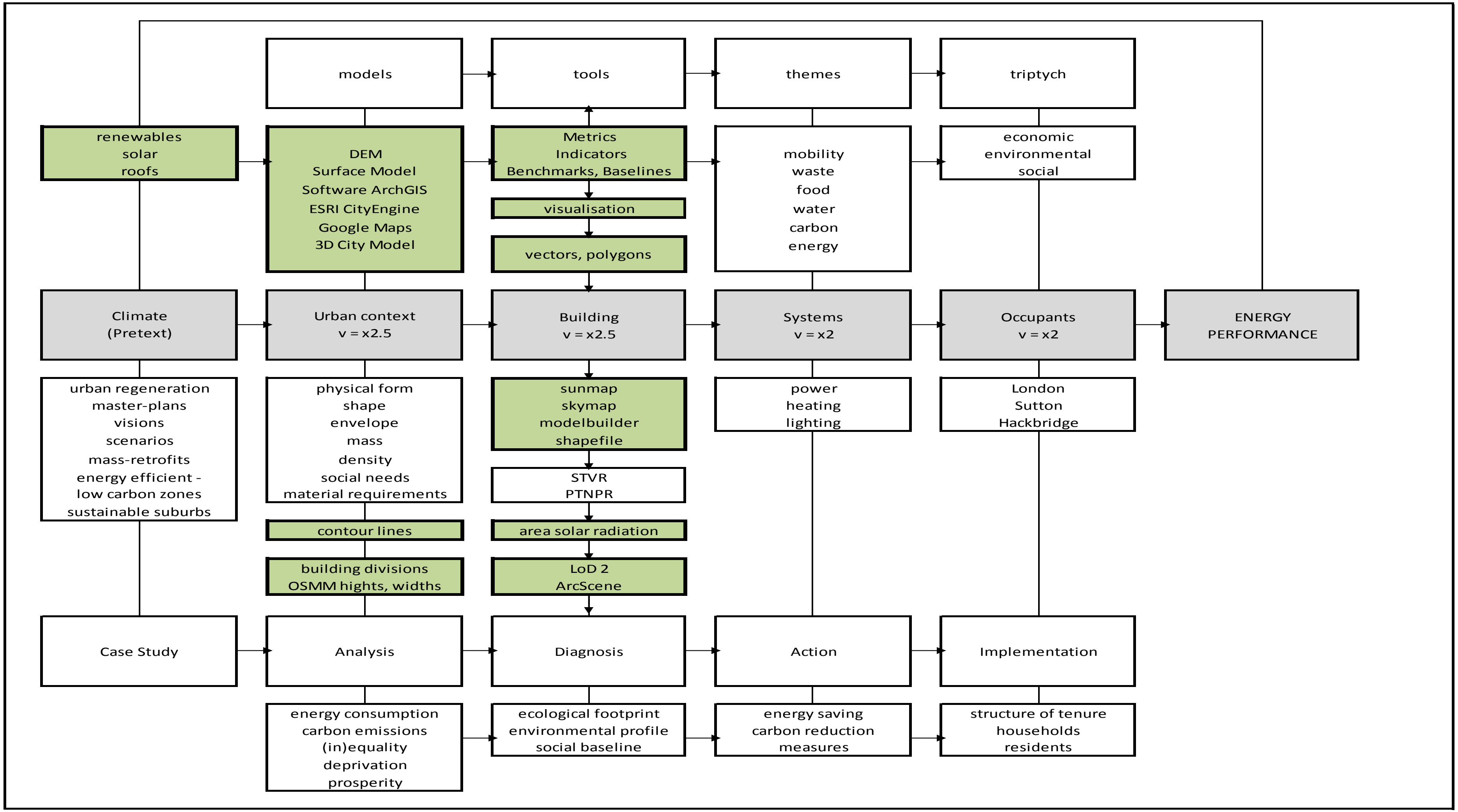


Figure 31: Morphological model (Adapted from Deakin *et al.*, 2015).

The morphological model represented in Figure 31 serves to reaffirm and present the key models highlighted in green integrated into the state-of-the-art analysis as part of an adaptation approach. For this model systematically contributes solar energy to the thermography of the thermal, lighting, power and heating systems of the structures that make up this environment and users which occupy them as the energy efficient-low carbon zones of sustainable suburbs.

3.5 Data Groundwork

Data is in turn obtained from Ordnance Survey (OS) and the national mapping agency for Great Britain. Likewise, the Open Street Map (OSM) building footprints are adapted from Deakin *et al.,* (2015), in relation to build up the model in LoD 2. Consequently, the roof pitch for each building is identified while the modelling of roofs is implemented with CityEngine. Hence the OSM footprints are supplemented with building widths and roof heights derived from OSMM data.

3.5.1 Building Height Attribute

The OSMM Building Height Attribute (2014) offers information about the height of a roof. However, information about the roof type is not indicated. Thus, the height of a roof is in turn calculated by subtracting the value for the base of the roof from the value for the highest part of the roof.

Using ArcMap, the building footprints are extracted from the *TopographicArea* feature class, which contains all polygons. The extraction is realized by using an attribute selection. In order to improve the extracted building footprints with 3D height information, the Building Height Attribute data is joined to the OSMM footprints using the unique ID each OS topographic feature has. The building footprints layer contains redundant buildings like garages or sheds. These features are removed from the dataset as they are not included in the analysis and would falsify the building heights. OS indicates that the currently available dataset, released December 2014, is an alpha release. The height values are automatically generated and may contain errors or inaccuracies. There are a number of potential error sources. For instance, if a tree overlaps a building, the height of the tree is in turn measured and assigned to the building as building height as illustrated in Figure 32.

Figure 32: Illustration of a building overlapped by a tree (Google Street View, 2015).

For the displayed semi-detached building, the OSMM Building Height Attribute states a total height of 21.4 metres for the left building part, whereas the right part has a more realistic height of 9.1 metres.

3.5.2 Hackbridge Building Widths

For the logic to calculate the roof pitch of Hackbridge suburb, the width of each building is required. Most buildings in Hackbridge districts are semi-detached or terraced houses and the division lines between the building parts represent their width. Building divisions are extracted from the TopographicLine feature class. The length of each line feature is in turn calculated based on its geographic position, given by the coordinates of its start and end point, and saved as an attribute. Figure 33 shows an OSMM building footprint overlaid by OSMM Building Division lines.

Figure 33: OSMM building footprint overlaid by division lines and satellite image of corresponding building in Bing Maps (Bing Maps, 2015).

The three longer lines include additions and therefore do not represent the width of the roof. Such building division features that do not represent the actual building width are deleted manually to exclude them from the examination.

3.5.3 Co-ordination Systems

For this examination, it is mandatory to load the OS Building footprints, OS Building Divisions and OSM footprints into the ArcMap. Being displayed together in ArcMap suggests there is an offset of over 100m between the OSM footprints and OS-datasets. This offset is in turn caused by the different projections that the datasets are stored in. The OS-datasets are referenced in the British National Grid GCS_OSGB_1936, whereas the OSM footprints are referenced in the WGS_1984_UTM_Zone_30N projection. Having datasets in the same coordinate system is a premise to perform analytical operations on them, vis-à-vis to the OS datasets which are projected to the WGS_1984_UTM_Zone_30N coordinate system. The ArcGIS tool *Project* provides the Geographic Transformation OSGB_1936_To_WGS_1984_Petroleum, which parameters are recommended by Ordnance Survey. In this regard, the transformation eliminates the offset.

However, the OpenStreetMap footprints are generated from satellite images. Also, one block of buildings in Hackbridge is represented by one feature, vis-à-vis to the OSMM data which is more precise. A block of buildings can be subdivided into several building parts, each represented by a single feature. As a result, for one OSM building footprint there can be multiple OSMM building footprints as illustrated in Figure 34.

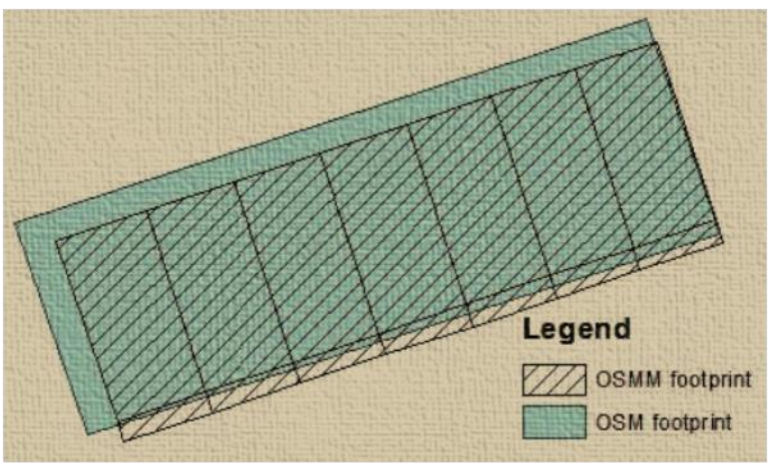


Figure 34: Single OSM footprint overlaid by multiple OSMM footprints.

Subsequently, the breakdown of the results of the executed joins in a matter of completeness yields mixed results. 98% of the building footprints in Hackbridge district got values for the roof height assigned, whereas only 67% obtained values for the building width.

As OSM building footprints are obtained from satellite images, some of them display the whole layout of a building, vis-a-vis to include additions and sheds that are detached to the actual building as illustrated in Figures 35 & 36 below. Since the roofs will be created automatically taking the footprints as base, these features have to be separated; so that the footprints define the extent of the actual roof. Likewise, the affected footprints are located using the satellite images provided by Bing Maps Bird's Eye and split manually.

3.5.4 Combination of the Datasets

OSMM building footprints and OSMM building divisions are integrated to the existing building footprints based on their spatial location. If an OSM footprint is intersected by multiple features, the numeric attributes of the intersecting features are summarized and the average value assigned to the footprint.

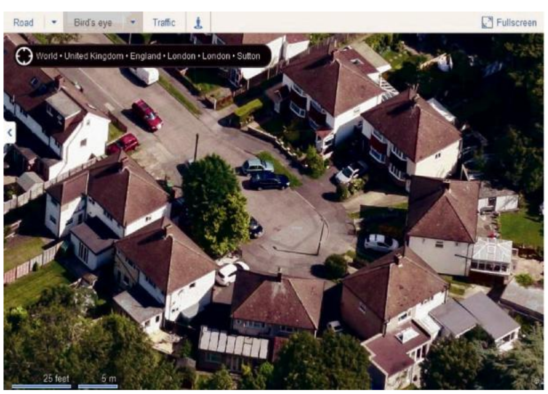


Figure 35: Satellite image of building additions. (Bing Maps, 2015).

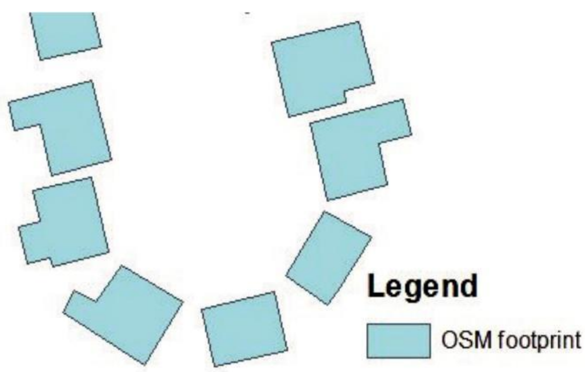


Figure 36: The OSM footprints

3.6 Calculated Roof Pitches

The roof pitch is in turn calculated for individual building footprint. Hence a new field in the attribute table is produced and for that field, the roof pitch values are calculated with the field calculator, applying Formula 1. However, it is estimated that 65% of the residential buildings roof pitch could be calculated as a result of missing width and height values for some footprints. As shown below in Figure 37, some of the calculated pitches are evidently wrong, in a matter of being too small or too large. However, the difference in the outcomes is clarified through the suggestions of inaccuracies of the OS Building Heights attribute.

footpolyAllInfo_Calculations

Building Typ	Building Age	house_flat_maisonette	Run	Rise	Pitch
F2	1930's St. Helier Estate, House and Maisonettes	semi	3,348974	3,6	47,06887
F2	1930's St. Helier Estate, House and Maisonettes	semi	3,319356	1,85	29,13254
F2	1930's St. Helier Estate, House and Maisonettes	semi	3,359781	6,3	61,92907

Figure 37: Illustration of calculated variable roof pitches.

3.6.1 The Mean Values for Hackbridge Buildings

As illustrated in table 8, the mean roof pitch for all calculated pitches for buildings of the same building type and age are calculated, vis-a-vis to recompense incomplete data and truncate outliers. The calculated mean roof pitch is in turn assigned to all buildings of a particular building age. This method centers on the situation that buildings of the same building age often exhibit similar building structures. Previous examination by Deakin *et al.,* (2015) designated the residential building stock in Hackbridge to 17 different building types and ages in order to scrutinize building age as a morphological indicator. As a result, their classification is in turn adopted for the calculation of roof pitches for this study. Furthermore, the standard deviation for all building ages of the calculated pitches is five degrees. Albeit the relatively low standard deviation indicates that the calculated roof pitches are close to the mean. Basically, all derived roof pitches are located within the range of typical roof pitches for the UK.

Table 8: The calculated mean values for Hackbridge venture.

Building Age and Type	Count Footprints	Count: No pitch calculated	Calculated Pitch (Degrees)	Standard Deviation (Degrees)
1930s Build	8	3	33.1	6.89
1930s Houses	122	72	32.9	6.15
1930s St. Helier Estate, House and Maisonettes	70	3	36.1	5.81
1950s Apartments	8	3	27.6	2.05
1990 Build Apartments	38	14	26.3	3.86
1990s Build Apartments and Houses	16	9	31.1	4.03
2000 Apartments	33	10	30.3	5.32
30s Semi-Detached	84	7	37.3	4.12

50s Apartm. + 70s Terr. Housing	7	0	33.4	5.76
80s Houses	8	4	39.1	11.95
Early 20th Century Houses	100	54	34.9	5.36
Early 20th Century Housing	24	10	39.2	6.60
Early 21st Century Housing	8	0	27.6	4.22
Late 18th Century Terraced Houses	2	1	39.8	0
New Build Apartments	8	8	0	0
Post War Temporary Housing	24	1	41.3	6.07
Sutton Housing Partnership	8	0	15.1	2.53

3.7 Building Hackbridge Structure in CityEngine

The prepared building footprints are loaded into CityEngine using the Shapefile import function. During the import process, the WGS 1984 UTM Zone 30N projection of the Shapefile is in turn adopted as coordinate system for the CityEngine scene. Together with the feature geometry of the Shapefile, also the feature attributes are imported. As illustrated in figure 38, they can be assessed individually by selecting a particular shape.

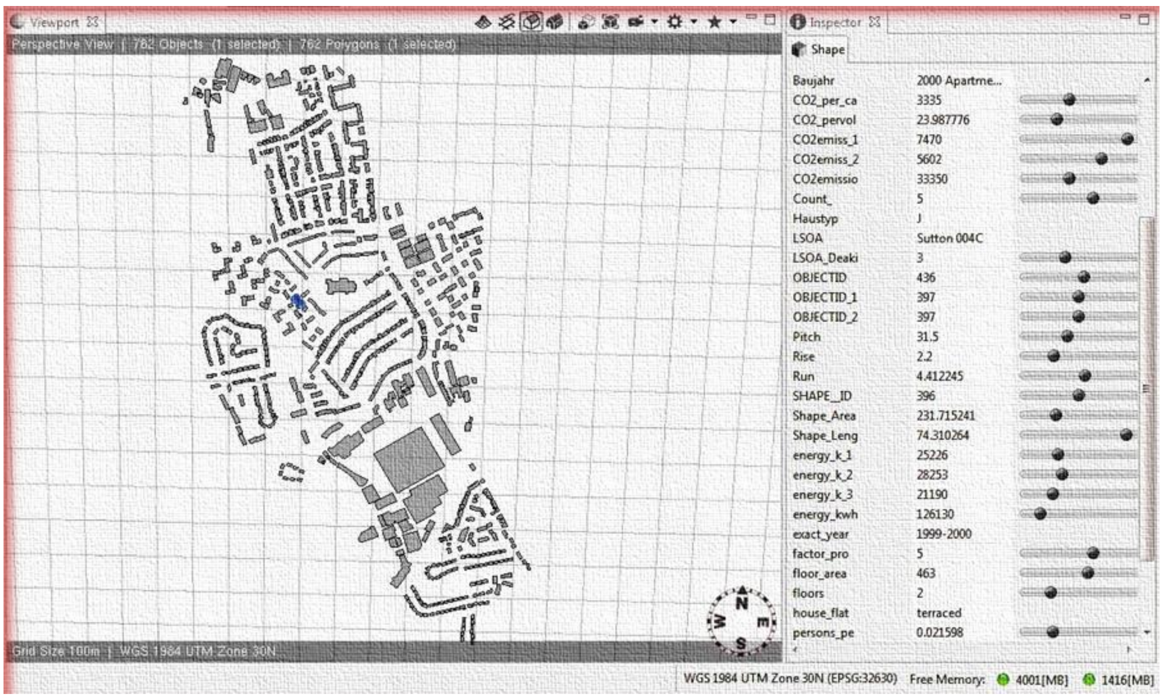


Figure 38: Imported building footprints in CityEngine and attributes for a selected shape.

Google Street View and Bing Maps Bird’s Eye are examined to select the appropriate roof type for each footprint. However, Figure 39 below illustrates the corresponding rule file is applied to the footprint, vis-à-vis to create the building.

3.7.1 Implemented 3D City Model

As a matter of fact, roof features are not considered in the rule files as they are varying for every building. Albeit influencing roof features like shed dormers or loft conversions are modelled manually after a rule file was applied, whereas chimneys and eyebrow dormers are not modelled as illustrated in Figure 40 below.

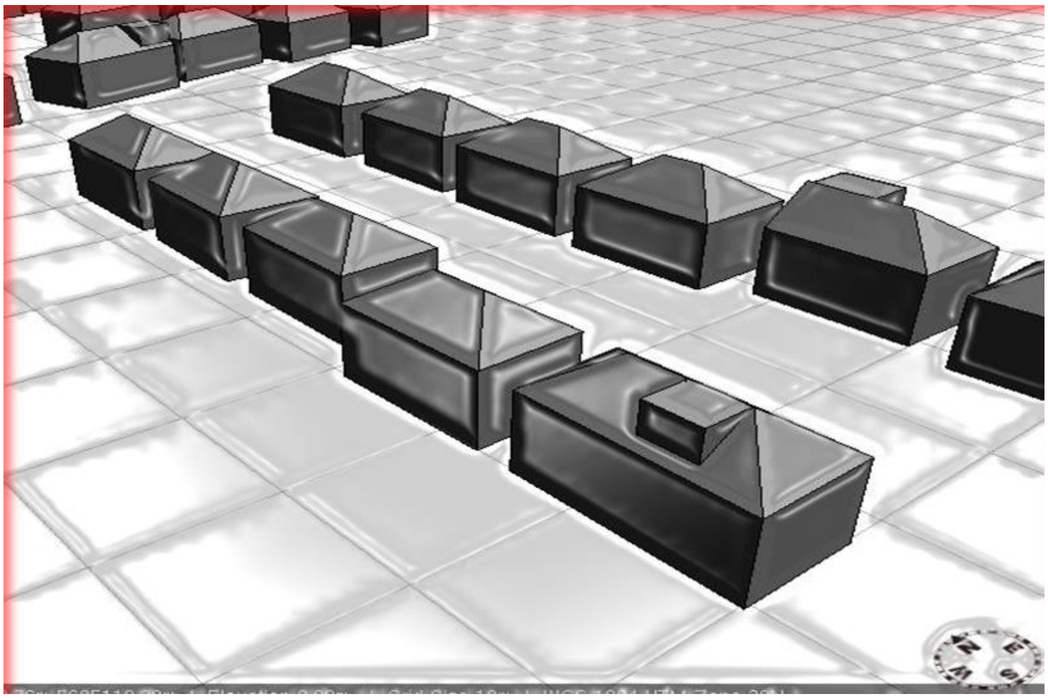


Figure 39: Axonometric view on modelled buildings in Meadow Walk.

For instance, two attributes i.e. *floors* and *pitch* are initialized. By means of giving them the identic name, they will access the correspondent column in the attribute table. Attributes have to be initialized to a specific value to ‘activate’ them (Esri R&D Center, 2015). In this case, both are set to zero and will obtain a value from their value within corresponding attribute. CityEngine allows the assessment of values from the features attribute table, vis-à-vis to examine them in the rule files. As a result, once the rule is assigned to shapes the attribute is set to a specific value.

In addition, building footprints exist of a simple polygon geometry in relation to which CityEngine refers to as lots. The lot rule extrudes all lots to three times the number of floors stored in the floors attribute. However, previous studies by Deakin *et al.,* (2015) examined three meters as an estimated floor height; in this way, the original building heights are in turn employed. Also, a rule always manipulates the current shape and creates new shapes for replacement. In this case, it is extruded and replaced with the created shapes *Building*.

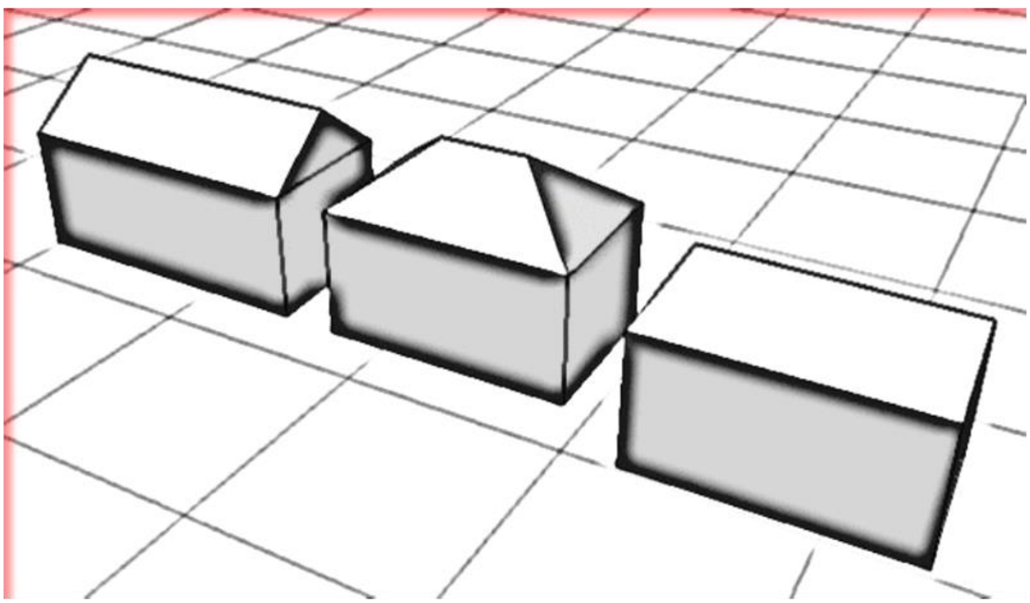


Figure 40: Axonometric view on the three modelled roof types.

Consequently, the Building rule uses the *alignScopetoAxes* operation to align the scope's axes parallel to the world coordinate axes. For this is necessary, vis-à-vis to examine the *comp(f)* operation successfully. With the *comp(f)* operation the *Building*-shape is divided into its faces. Faces are selected by analyzing their normal compared to the local coordinate system. Here the top face and all vertical faces are selected and transformed into new shapes. The shape created from the top face is named *Roof* and further processed.

Finally, the roofGable operation is assigned to the *Roof* shape. Thereby a gable roof with the pitch accessed from the attribute table is in turn built on top of the roof-face.

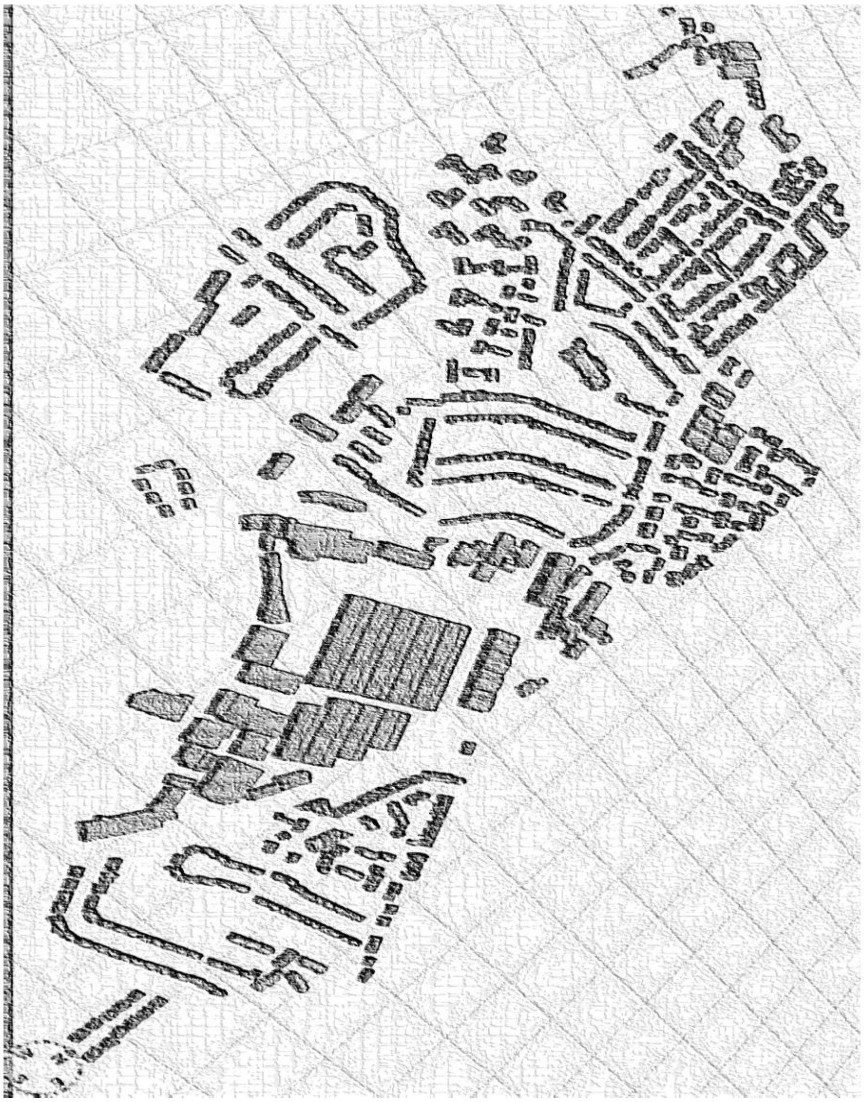


Figure 41: Axonometric view on the 3D model of Hackbridge.

Moreover, the creation of hip roofs is in turn similar to the described approach for gable roofs, but uses the roofHip operation instead of the roofGable operation. Similarly, flat roofs are modelled by extruding the footprints without creating a roof structure as illustrated in Figure 40. Therefore, no overhangs are considered for any roof as the OSM footprints are created from satellite images, vis-à-vis to already display the contour of the roof.

3.8 Evaluation of ArcGIS-Based Solar Energy

The direct solar energy is in turn calculated for this study using a sunmap. However, sunmaps are raster representations of the position of the sun in the sky for every hour of the day and every day of the year. Albeit the sunmap is divided into multiple sun sectors as a result of the given latitude and time span. In this logic, individually sun sector originating from the solar energy is calculated discretely.

In addition, Fu and Rich (1999) suggested that skymap is the hemispherical view of entire sky divided into sky sectors. For the sky sectors are distinct by zenith and azimuth angles. However, the diffuse solar energy that appears scattered originates from all sky directions and is in turn calculated for each sky sector. Also, solar energy values are calculated, vis-à-vis overlaying the viewshed on the sunmap and the skymap, and summing up all insolation originating from unobstructed sky directions.

Consequently, the sky size defines the resolution of the viewshed, sunmap, and skymap rasters. Hence a higher sky size results in a higher resolution, but likewise in a considerably higher calculation time. For urban areas and a long-time period (e.g. one year), a sky size of 200 (columns and rows) is recommended (Esri, 2014).

As a matter of fact, atmospheric factors are responsible for diffuse solar energy. This shows that *Area Solar Radiation* tool considers atmospheric factors insofar that the diffuse proportion of solar energy can be declared. However, the value depends upon the atmospheric condition for the location. For generally clear skies, a default value of 0.3 (30%) is proposed. Similarly, two different models for the distribution of diffuse radiation are provided. Likewise, the uniform diffuse model assumes same incoming diffuse radiation from each sky direction. However, the standard overcast diffuse model offers incoming diffuse radiation varying with the zenith angle, vis-à-vis the amount of radiation reflected away by the atmosphere which can also be considered. As a result, possible values range from 0 (no transmission) to 1 (all transmission).

3.8.1 Solar Energy Calculation Process

Consequently, the *Area Solar Radiation* tool gleans incoming solar energy from an input elevation raster. For the reason to be practical with the *Area Solar radiation* tool, the city model multipatch features are converted to a raster surface with a resolution of 0.5 meters as demonstrated in Figure 42. Besides, the z-value of the multipatch feature is determined for the center of each raster cell and assigned to the raster as elevation value.

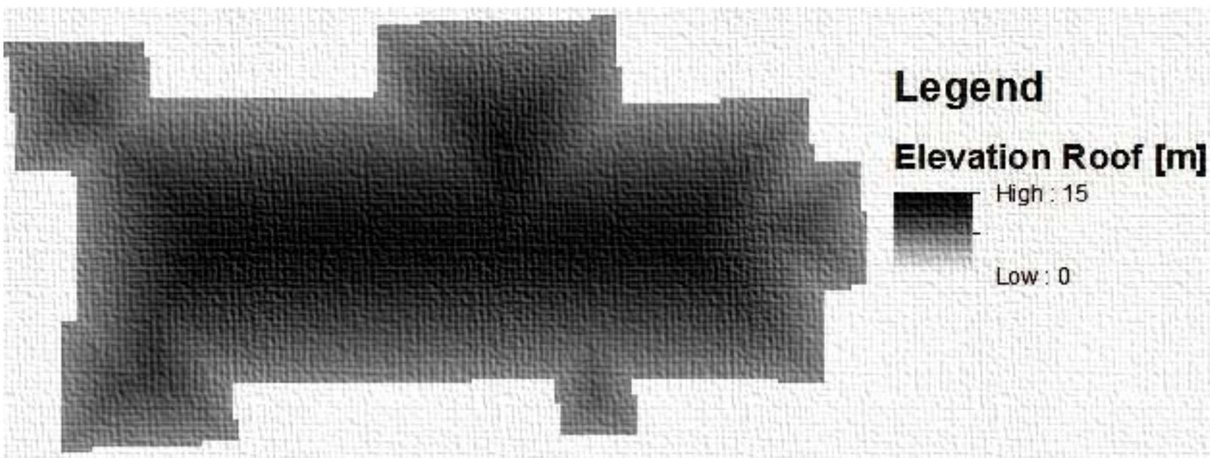


Figure 42: Raster representation of a multipatch feature in ArcScene.

More importantly, the accuracy of the calculation depends on the raster size of the input DEM and the chosen sky size. In this instance, Chow *et al.,* (2014) suggested that a cell size of 0.5 meters is advisable for urban areas, as this shall be accurate enough to describe the urban structure and the calculation time remains realistic. Thus, a raster resolution of 0.5 meters is in turn chosen, vis-à-vis to perform the calculations.

The elevation data for Hackbridge suburb is in turn gleaned from the Ordnance Survey Terrain 50 contour lines, as the OS Terrain offers free elevation data for Great Britain. By way of using ArcGIS, the contour lines are interpolated and transformed to an elevation raster. Albeit, the raster is projected to UTM Zone 30N and clipped to the extent of the Hackbridge model.

In addition, the elevation values of both rasters are summed-up cell by cell in relation to obtain the actual terrain for Hackbridge, including building heights. Although this terrain model is evaluated as input for the *Area Solar Radiation* tool. In this regard, the slope and aspect of the roofs is gleaned from the DTM. Moreover, the incoming solar energy is calculated for the whole year with a time interval of 14 days ascertained for the calculation of sky sectors for the sun map. In this situation, the time interval throughout a day is set to 0.5 hours.

For the intellect to examine the atmospheric conditions for London, the proportion of diffuse radiation flux is set to 0.55. Albeit this value is calculated as ratio between direct and diffuse solar radiation from long term measurements from the freely available NASA Surface meteorology and Solar Energy database that is available for particular locations worldwide, and demarcated by their latitude and longitude (Hackbridge: 51.5, 0.5). As a matter of fact, the solar energy parameters provided in the database are gleaned from satellite images and contain monthly averages from 22 years of data measurements from 1983 to 2005. However, the Insolation Clearness Index clarified as the fraction of radiation that passes through the atmosphere for London is 0.4. Thusly, the specified atmospheric parameters are annual averages which vary between the seasons.

As a result, the solar energy is in turn calculated for both diffuse radiation models. Also, the peak values obtained by calculating with the standard overcast model are about 1070 kWh/m² range for a whole year as illustrated in Figure 43. On horizontal surfaces, for instance a flat roof; the calculated energy values range around 1000 kWh/m² for the total year. By way of applying the uniform diffuse model, the obtained peak value is 61 kWh/m² less. Likewise, the radiation values for horizontal surfaces are around 60kWh/m² lower.

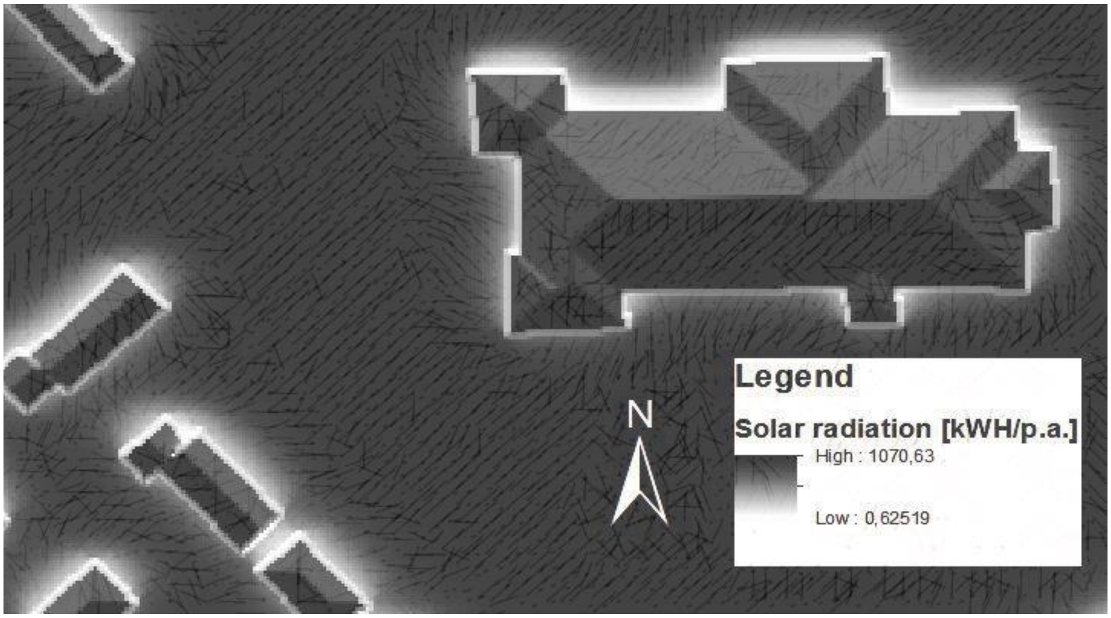


Figure 43: Extract of the solar energy raster displaying the calculated yearly solar radiation.

Upon the logic to verify the calculation results, they are compared to the solar energy database included in the Photovoltaic Geographical Information System (PVGIS), which is provided by the European Commission, Joint Research Centre Institute for Energy and Transport. However, the solar radiation data provided in PVGIS is gleaned from ground measurements and calculations based on satellite data. For the geographic position of Hackbridge (51.5°, 0°), the average sum of global radiation/energy received on a horizontal surface is in turn given as 1100 kWh/m² (PVGIS, 2012). Albeit taking the PVGIS data as reference, the standard overcast model provides more accurate results and is in succession chosen for the further analysis.

In this assessment, the output raster contains the calculated solar energy values for each location in WH/m². Also, the value obtained is converted to kWh/m² by way of dividing the solar energy values of each cell by 1000. By the effect of using *SolarRadiationRoofZones* model offered in the *3DCitySolarTools* toolbox, the results from the radiation raster are applied to the multipatch roof features as shown in figure 44. Subsequently for each roof side, the average radiation of the raster cells that lie within a particular roof feature are calculated. As a result, the average yearly solar radiation for each roof side is ascertained.

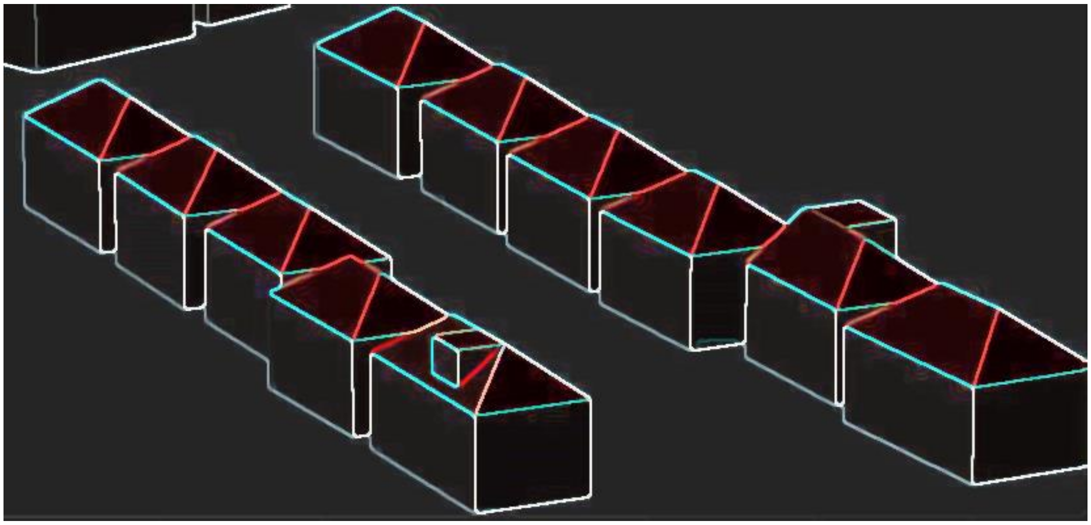


Figure 44: Yearly radiation values assigned to multipatch roof features.

3.8.2 The ArcGIS ModelBuilder

Accordingly, the ArcGIS ModelBuilder is established to combine the processing steps to create the radiation raster into one workflow as illustrated in Figure 45. As a matter of fact, the model takes a DTM and a multipatch city model as input and processes both so as to calculate the annual radiation in kWh/m². In view of combining geoprocessing tools with the ModelBuilder, the output generated by an operation can be evaluated as input for subsequent operation.

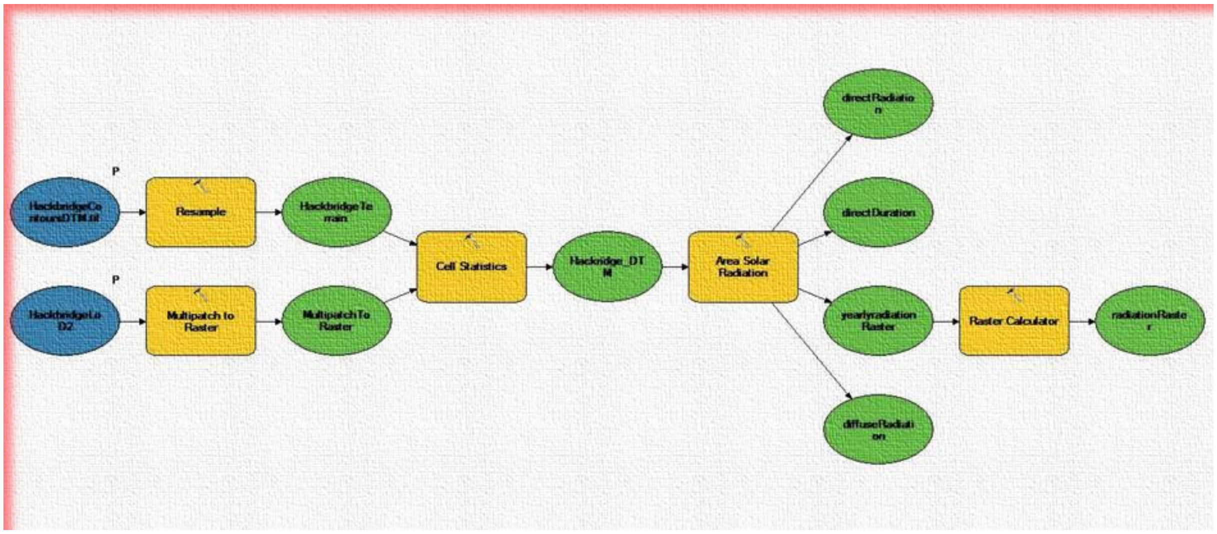


Figure 45: Processing steps shown in ArcGIS ModelBuilder.

3.9 Summary

As a matter of fact, it is the significance of this renewable energy basis in the retrofit, that this study wants to uncover the particular contribution it makes to the retrofits, levels of energy consumption and attributed to the sustainability of the suburb and contribution this in turn makes to tackle global warming as part of a climate change adaptation strategy. This means that for this approach renewables are the key components of the mass retrofit study as it promotes to reduce levels of energy consumption and carbon emission, vis-à-vis to establish energy efficient-low carbon zones as an exercise in the development of sustainable suburbs that not only tackles global warming but combats climate change.

Consequently, the light of this procedural modelling approach captures the potential contribution solar panels installed onto the roof of Hackbridge buildings in LoD 2 by allowing renewables to develop the environmental sustainability of energy efficient low carbon zones and the residential property sector as part of a climate change adaptation strategy. Also, it enables this method to potentially offer the key green values it makes to levels of energy consumption and rates of carbon emission that sets a standard of "sustainable suburbs".

In addition, the next chapter shall present the findings of how it is proposed this should be applied within the context of the mass retrofit under scrutiny and use this analysis as a way to measure the improvements any plans occupied to produce solar power for the principles of heating above the standard. It shall then go on to clarify these findings by reflecting on assessment and appraising to point to which these above the standard developments do raise the levels of energy consumption and carbon emission into an energy efficient-low carbon zones and establish the position of a sustainable suburb capable in that impression to confronts global warming and associated level of climate change as a result of "renewables-based urban morphology" and procedural modelling approach established.

Chapter Four

4.0 Analysis

4.1 Introduction

The analytical section of this thesis demonstrated the influence of urban morphology on building energy consumption and draw a connection between urban morphology, solar energy and renewable energy technologies. As Deakin *et al.,* (2012a, 2012b, 2013) developed a 3D model of urban morphology that enables an integration of key components into the urban morphology of energy efficient-low carbon zones, this in turn permit the procedural modelling approach that forms a principle constituent of this study to clearly substantiate the influence of renewable energy into the development of energy efficient-low carbon zones. The results presented in this study are clearly integrated into the current state-of-the-art city model of Deakin *et al*., (2014, 2015) to perform a morphological analysis in terms of the contribution of solar energy.

4.2 The Hackbridge Venture

The London Borough of Sutton wants to become the UK's first 'truly sustainable suburb' (One Planet Sutton, 2014). The project 'One Planet Sutton' was launched in 2009, as a community led project, supported by BioRegional as a project partner. One Planet Sutton aims to reduce the ecological footprint of each resident to a sustainable and globally fair level. A number of targets were released, covering a sustainable waste management, ecological food management, sustainable transport, sustainable water management and cutting carbon emissions of buildings.

To reduce carbon emissions from buildings, Sutton wants to become a 'zero carbon building' suburb. The energy circle (consumption and production) of zero carbon buildings does not emit CO_2. One Planet Sutton (2014) repeat their target, that the amount of CO_2 produced by the borough's buildings shall be reduced through energy efficiency and renewable energies. The London Borough of Sutton and Bioregional presented an area-based strategy for achieving zero carbon buildings. The report focuses on Hackbridge, a suburb within the London Borough of Sutton. Using Hackbridge as an example for a zero-carbon suburb, it should serve as model for other suburbs, helping them to become sustainable suburbs themselves (BioRegional Development Group, 2011). The report considers solar photovoltaic panels as renewable energy system. This thesis seeks to identify the potential of solar energy and how it would affect energy consumption and carbon emissions.

4.2.1 Hackbridge Features

Hackbridge is a largely residential suburb with a population of about 8,000 inhabitants. The Hackbridge housing stock compromises a broad cross section of building types and ages. It ranges from late nineteenth century terraced houses over 1930s semi-detached houses and 1950s built social housing to 1990s built properties Houses in different building ages vary significantly in terms of energy performance. Late nineteenth century buildings are poorly insulated and ventilated where newer built houses generally are in better condition. A smaller number of houses built 1960 and 1980 shows different behavior in energy performance. Contrary to houses and semi-detached houses, 1950s and 1990s built properties consist mostly of flats.

Hackbridge contains a wide spectrum of social characteristics, so are one of the most deprived and one of the least deprived areas in England located in Hackbridge. To perform district level analysis, Deakin *et al*., (2014) applied their results to five lower layer super output areas (LSOAs) within the residential building stock of Hackbridge. LSOAs are geodemographic areas based on neighboring postcode areas which are grouped in a way that they exhibit similar socio-demographic characteristics. By analyzing LSOAs the focus can be laid on occupational behavior.

4.3 Analysis of Solar Energy Calculations

The contribution solar panels installed onto the roof of buildings make to levels of energy consumption and rates of carbon emission is examined via the implementation of the photovoltaics as earlier discussed in the previous chapter. Nevertheless, the formula offered by PVGIS © European Communities (2012) is scrutinized to calculate the energy output in kilowatt-hours (kWh) of a photovoltaic system mounted on individual roof structure of Hackbridge suburb.

The Energy which is in (kWh) = A * r * H * PR (2)

Whereas; A = Total solar panel area (m^2)

r = Solar panel yield (%)

H = Annual average solar radiation (kWh/m^2)

PR = Performance ratio

Subsequently, the above formula is carefully studied to calculate the energy output for individual roof structure located within Hackbridge district, and all calculations are carry out on the features attribute table in ArcScene as this examination adopts the procedural modelling concept. In analyzing the urban morphology of Hackbride suburb, the total solar panel region is expressed as the available area of individual roof surface.

Available Area (m^2) = Total Area – Small dormer * 5 – big dormer *10 (3)

Also, the *CalculateGeometry* operation is examined to ascertain the area of roof surfaces in accordance to their discrete geometry. For the aim to achieve precise outcomes in a matter of existing roof range, the region occupied through dormers is captured. However, the Eyebrow dormers were not exhibited; as a result, their effect on conventional solar energy is insignificant as the existing capacity for photovoltaics lessens should a roof contains dormers. However, the amount of big eyebrow dormers and smaller eyebrow dormers located on a specific roof are calculated as a result of examining satellite images in Bing Maps Bird's Eye. Likewise, for individual small eyebrow dormer, 5m² are subtracted from the available area. However, ineffectual range of 10m² is appraised for bigger dormers.

In expressing solar energy as a renewable energy, Dobos (2014) states the outcome of a solar panel as the ratio of the electrical power (kwp) of one solar panel divided by the area of that panel. He goes on to say that: PVWatts calculator, an online tool to estimate energy production of photovoltaic systems operated by the United States National Renewable Energy Laboratory (NREL), indicates the efficiencies of 'typical' polo- or mono-crystalline silicon modules between 14% and 17%. However, by introducing the *SunArea* project apprehended by the University of Applied Sciences Osnabrück, to map the solar potential of roofs, a solar panel outcome of 15% is presumed.

Thus, *Performance ratio* (PR) is specified by Dobos (2014) in capturing the performance of photovoltaic components make to levels of energy consumption and rates of carbon emission. However, He goes on to suggest that there are loads of influences apart from solar dynamism that have consequential impacts on electrical energy supplied by means of photovoltaics, as units performance is dependent on the site, the technology, and sizing of the system. Hitherto ascertained impacts on solar radiation, like slope and orientation are not deliberated for the PR. For its simulation tool, the PVGIS reflects the following, not extensive, list of losses (estimated impact in brackets):

- Air-temperature and low irradiance losses (~ 7%)

- Inverter and cable (AC, DC) losses (~ 15%)

- Shading, Soiling, Snow losses (~ 5%)

The impacts of shading within the morphology of an energy efficient-low carbon zone of Hackbridge venture, in relation to the neighboring borough texture and roof topographies have been ascertained by means of calculating the solar energy appraisals. Albeit the shadows of chimneys, eyebrow dormers and vegetation (majorly trees) are not thus far deliberated, as they have not been exhibited. Hence, losses due to shadings are taken into account, when defining the PR.

Consequently, a research by Jahn *et al.,* (2000) examined the operational data of various photovoltaic systems located worldwide to provide technical information about their performance. Their investigation suggested that a performance ratio of 0.6 to 0.8 can be estimated. In addition, Dobos (2014) predicted the PR to increase over the next years, and in examining Hackbridge suburb in this instance, and panels installed with a tilt of 35°, the PVGIS offers combined system losses of 23.6%. Also, with alternative photovoltaic performance estimator, the PVWatts calculator applies a PR of 0.77 to consider system losses for the calculation. Upon these constitutional tools, a PR of 0.77 is in turn adopted for the solar energy output and the calculation is executed in ArcScene. Similarly, a new field is added to the attribute table and while using the *FieldCalculator,* the energy output for individual roof side is in turn calculated grounded upon its region and average annual radiation.

E = [AvailableArea] * 0.15 * [AnnualSolarRadation] * 0.77 (4)

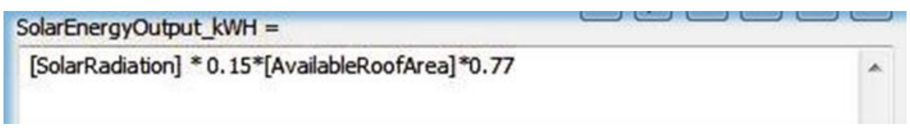


Figure 46: Calculations implemented in the FieldCalculator

In view of this, Formula *2 is* applied to calculate the energy output of photovoltaics installed on the rooftops of Hackbridge suburb by demonstrating roof structures as a principal component of energy consumption and carbon emissions in buildings as vital elements in the drive towards the development of energy efficient-low carbon zones. Also, figure 46 clearly illustrates the implementation of Formula 2 in ArcScene’s field calculator. Albeit the formula draws upon the attribute values for the yearly solar radiation and the region offered for the installation of solar panels of individually roof feature, articulated as square brackets.

4.4 Ascertaining Appropriate Roof Structures

The roof structures of Hackbridge suburb needs to meet two fundamentals that is associated to analyzing a sustainable procedural modelling concept for installation of photovoltaics. For this reason, the rooftop region must be sufficiently large and a minimum amount of solar radiation must be received. This prerequisite shall allow the urban morphology of the mass retrofit establishing the matter of this examination to render roof structures a principal component of energy consumption and the carbon emission. Otherwise, the key drivers that renders roof structures a crucial element in the development of energy efficient-low carbon zones as sustainable suburbs will remain unsubstantiated and shall portray the photovoltaic system unproductive and non-profitable.

Consequently, the solar potential analyzed by the cadastre of Osnabrück ascertains an obtainable area of 15m² as the minimum region for a roof to be suitable for the installation of photovoltaic modules. Roofs that fulfil that prerequisite and receive a yearly radiation of 800 kWh/m² or more are classified as well suited for photovoltaic panels. Roofs with a minimum area of 15m² and a yearly radiation of over 950 kWh/m² are rated as very well suited. Similarly, all other roof areas are excluded as the installation of photovoltaics on them would not be cost efficient (City of Osnabrück, 2015). However, a threshold of at least 900 kWh/m² received radiation per annum is ascertained for the calculation of potential energy generated from photovoltaics for Hackbridge suburb. In this means, some potential roofs are neglected, though a higher output of the installed panels is confirmed while the minimum area of 15m² is adopted.

The energy output that ascertained the amount of solar energy to generate from the solar panels installed on the roof structures of this borough is calculated for all rooftops appearances that meet the above condition using Formula 2. Likewise, the appropriate roofs are selected using an attribute selection and a minimum threshold of 900 kWh/m² is relatively high. However, table 9 illustrates that even systems received around 800 kWh/m² can be cost efficient. As a result, it shall yield to a much higher energy output, as more roofs would be utilized. Also, table 9 demonstrates the energy output for different thresholds to exhibit the potential of photovoltaics for Hackbridge suburb.

Afterwards, installing photovoltaics is costly and it is unlikely that all roofs are examined. Albeit the calculations apprehended in this thesis is based on a city model which contains possible inaccuracies that key to a margin of error up to 10%. On these grounds, the threshold of 900 kWh/m² was chosen. Table 9 shows the energy output for different thresholds to show the potential of photovoltaics for Hackbridge suburb. Upon a threshold of 900 kWh/m², the calculated energy output is 4.5% higher than the one assumed in the Energy Options Appraisal.

Table 9: Energy output for different thresholds of minimum yearly solar radiation

Minimum yearly received Radiation	Generated Energy for 1m² panel with indicated insolation	Energy output residential buildings Hackbridge
800 kWh/m²	92.4kWh	5,853,592 kWh
850 kWh/m²	98.2 kWh	4,840,157 kWh
900 kWh/m²	103.95 kWh	4,024,316 kWh
Energy Options Appraisal (Bioregional Consulting, 2008)	Potential Savings Photovoltaic: 3,849,005 kWh	

4.5 Morphological Examination

This subdivision clearly uncovers the influence of renewable energy technologies in drive towards the development of energy efficient-low carbon zones as sustainable suburbs which logically fashions to prevent global warming and contest climate change as part of an adaptation strategy. It critically appraises the 3D data and information obligatory to calculate the amount of solar energy: that calculated solar radiation output is generated from the solar panels installed onto roof structures of Hackbridge suburb that in turn permits the procedural modelling tactic that customs a standard constituent of this examination to evidently substantiate the impact of solar energy in the progress of energy efficient-low carbon zones.

4.6 Energy Savings and Carbon Reductions

The corresponding carbon emission reductions are calculated as a result of knowing the potential energy savings for each footprint. Figure 47 illustrates that the installation of photovoltaics on suitable residential buildings in Hackbridge could save 4,024,314 kWh of energy, which would reduce the current CO_2 emissions by 8.3%.

However, the demonstrations of Deakin *et al*., (2015) ascertained the energy savings and carbon reductions that is associated on the savings calculated for the retrofit options visualized. This is achieved by way of an area-based analysis, linking levels of energy consumption and carbon emissions to the structure of tenure and the connection this in turn has to the housing market. Consequently, table 10 illustrates the calculated results for the five LSOAs. Seeing the figures per LSOA, it can be gleaned that energy saving and carbon reductions are interdependent. Higher energy savings result in higher carbon emission reductions.

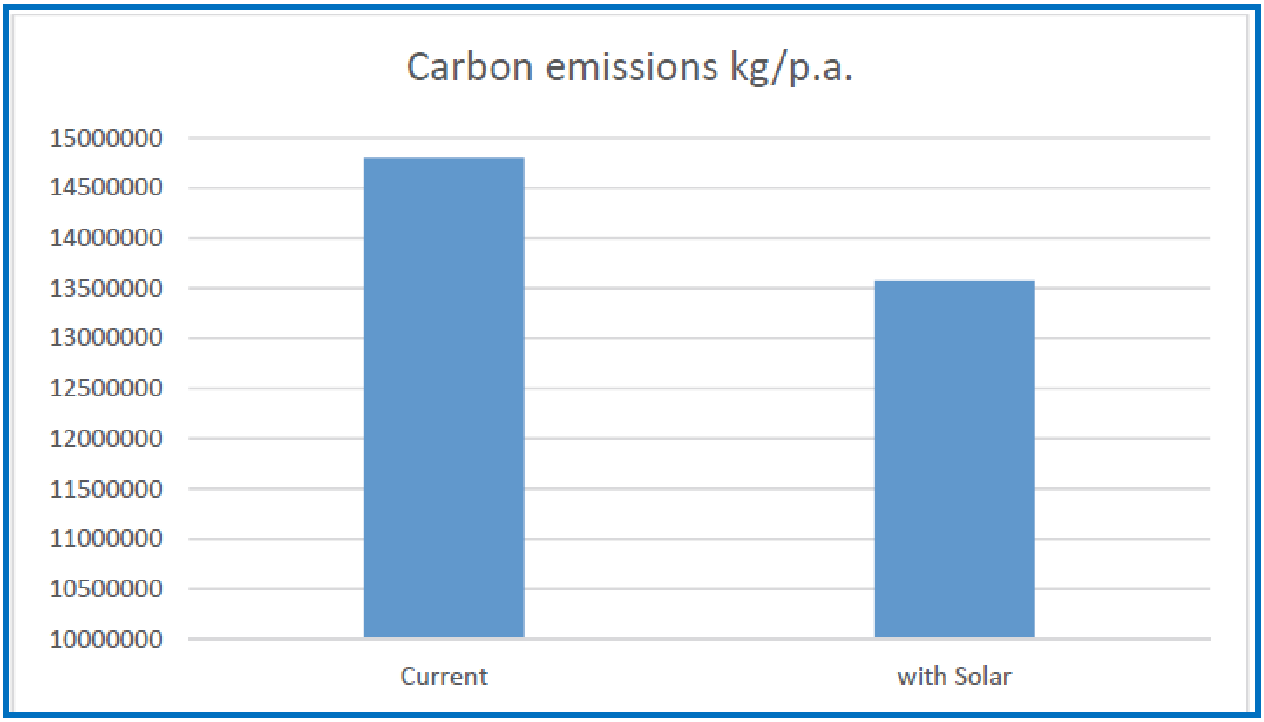


Figure 47: Carbon emission (kg/p.a.) with and without solar power

Table 10: Energy consumption, CO_2 emissions and the contribution of solar power by LSOA

	LSOA 1	**LSOA 2**	**LSOA 3**	**LSOA 4**	**LSOA 5**
Current Energy consumption	6,733,319	14,644,009	5,576,413	13,140,448	8,079,019
Energy Output of Photovoltaics (kWh)	533,545	1,030,407	502,228	1,319,159	535,859
Percentage	7.9%	7%	9%	10%	6.6%
Current CO_2 Emissions	1,904,109	4,684,583	1,657,453	4,002,471	2,176,338

CO_2 savings	153,810	338,565	150440	403,067	150,028
Percentage	8%	7.2%	9.1%	10.1%	6.8%

Using the model offered in this examination, it is possible to apprehend the contribution solar energy creates to levels of energy consumption and rates of carbon emission which hitherto remains unsubstantiated. Hence, Figures 48 & 49 ascertained the energy savings and carbon reductions that are associated to the savings calculated for the two suggested retrofit options. Albeit the graphs presented below also highlight the influence of solar energy for the particular LSOAs.

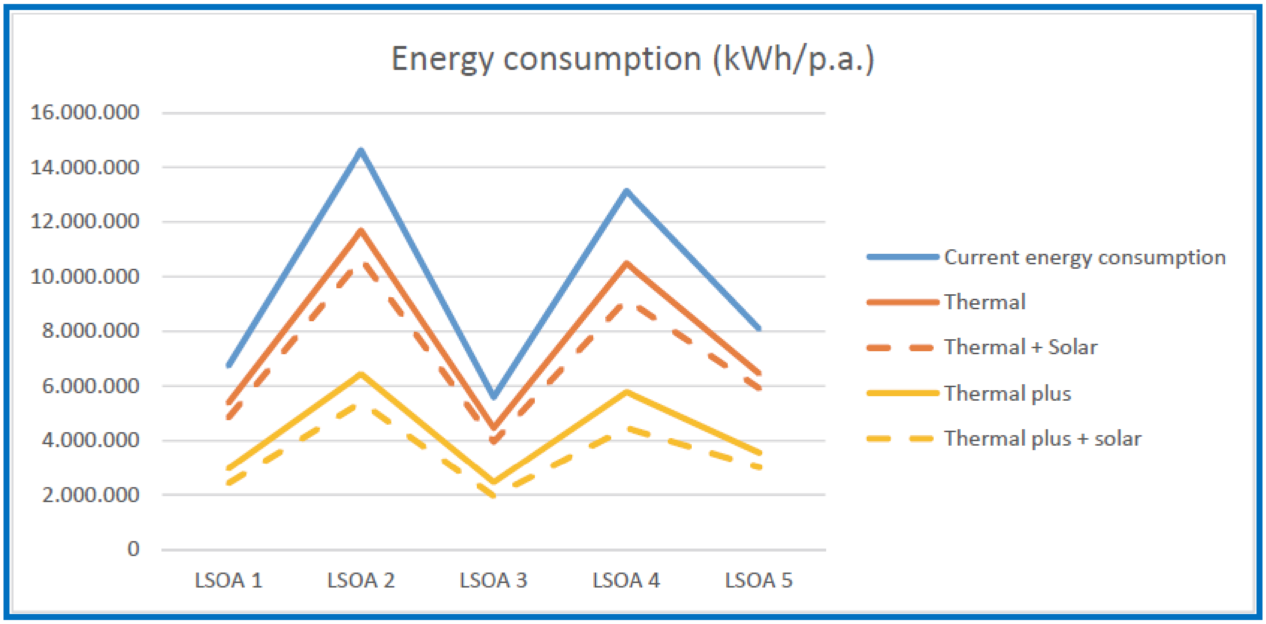


Figure 48: Energy saving by type of retrofit

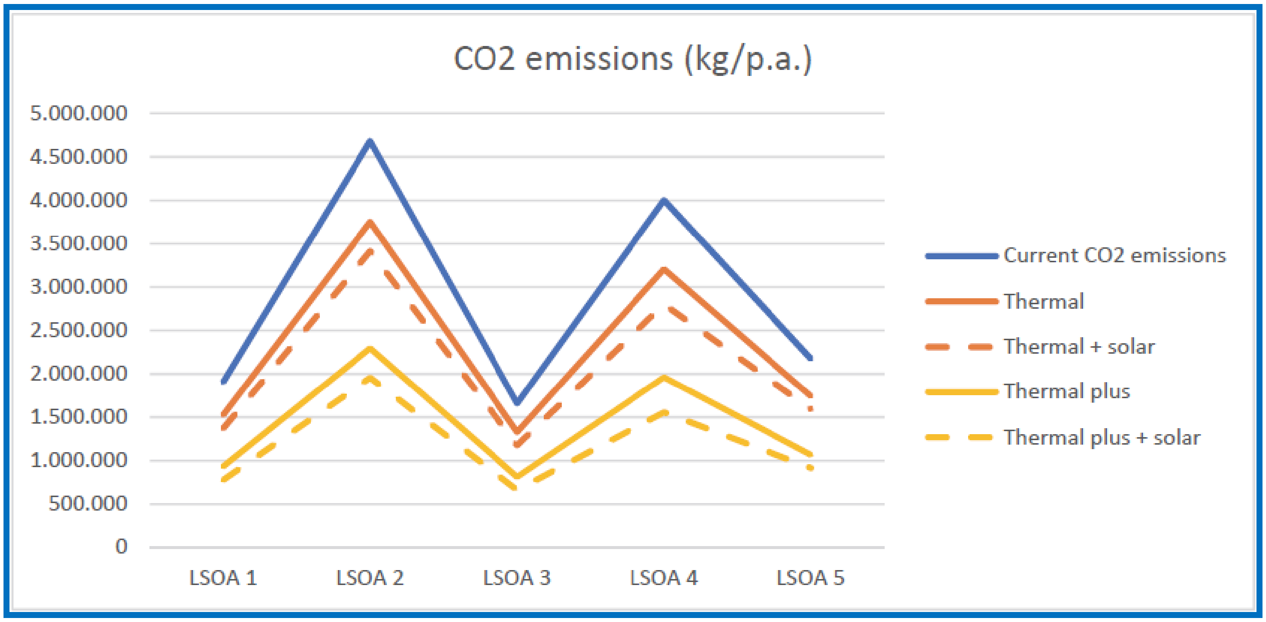


Figure 49: CO_2 reduction by type of retrofit

4.7 Analysis of the Appropriate Roof Area

A research article by Carneiro *et al.,* (2009) presented the area of roofs that is appropriate for the installation of photovoltaics as a parameter for "solar admittance on urban fabric". Albeit this can be expressed as a ratio between the suitable roof area and the total roof area. Building footprints with no suitable roof area have a ratio of 0, whereas 1 indicates a completely available roof. Figure 50 demonstrates the suitable roof area ratio for buildings in the north of Hackbridge Suburb. However, such exploration is associated to other morphological factors so as to discover possible influences on the suitable roof area ratio. Thusly, two influences specified by Carneiro *et al.,* (2009) are the density of buildings in terms of overshadowing and the building age.

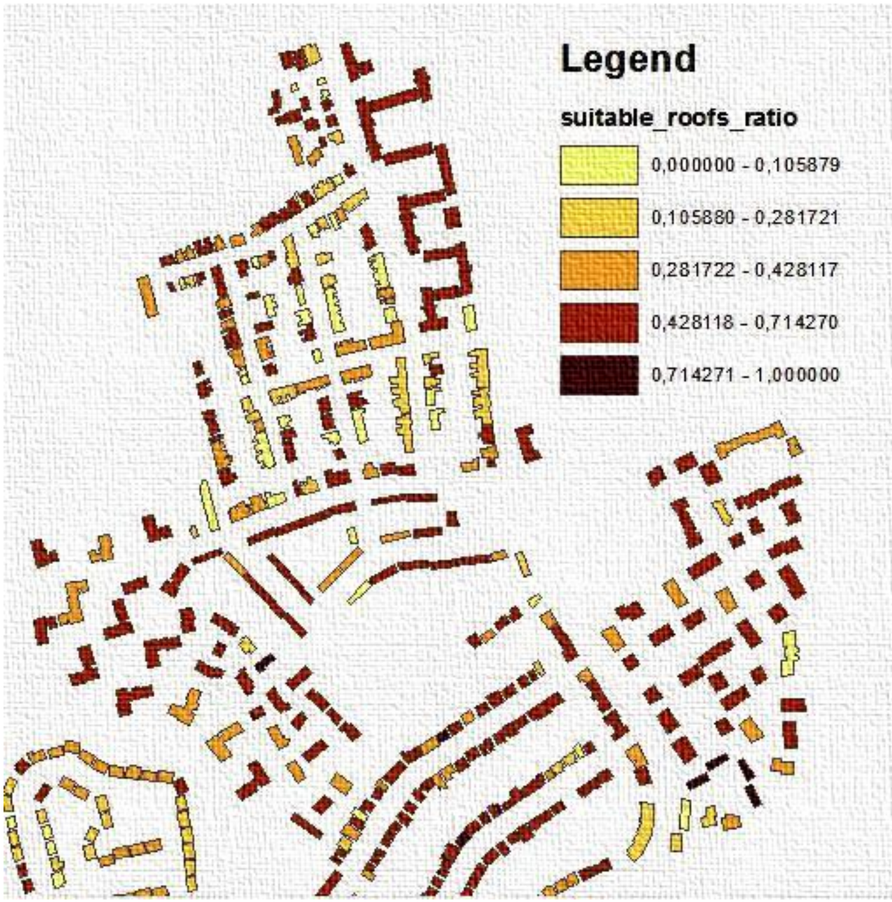


Figure 50: Suitable roof area per building

Also, previous studies by Deakin *et al.,* (2015) offered that suburban character of Hackbridge district compromises many smaller houses. The suburban character of Hackbridge is represented by a high PVTVR, because a great number of the buildings do not have non-passive zones as they are too small for it, which makes overshadowing unlikely. Albeit Carneiro *et al.,* (2009) examined the surface to volume ratio (STVR) as measure of compactness, whereby a small STVR indicates higher compactness. Hackbridge suburb with its suburban character has a consistently high STVR of about 0.58. Even though the STVR stays the same, the suitable roof area varies for the different LSOAs. Both ratios (PVTVR and STVR) indicate that overshadowing by other buildings does not affect solar admittance of buildings in Hackbridge suburb considerably.

Subsequently, buildings of the same building age often exhibit similar characteristics. As Figure 51 demonstrates; the ratio of suitable roof area to the total roof compared to the building ages of buildings reveals that newer buildings have a better solar admittance. However, this could reflect the trend to consider the utilization of solar gains in the urban planning process. As overshadowing effects by surrounding buildings are negligible for Hackbridge suburb, the orientation and tilt of roofs is the main influence on the solar admittance. Houses with unobstructed, south-facing roofs have the best preconditions to produce solar energy.

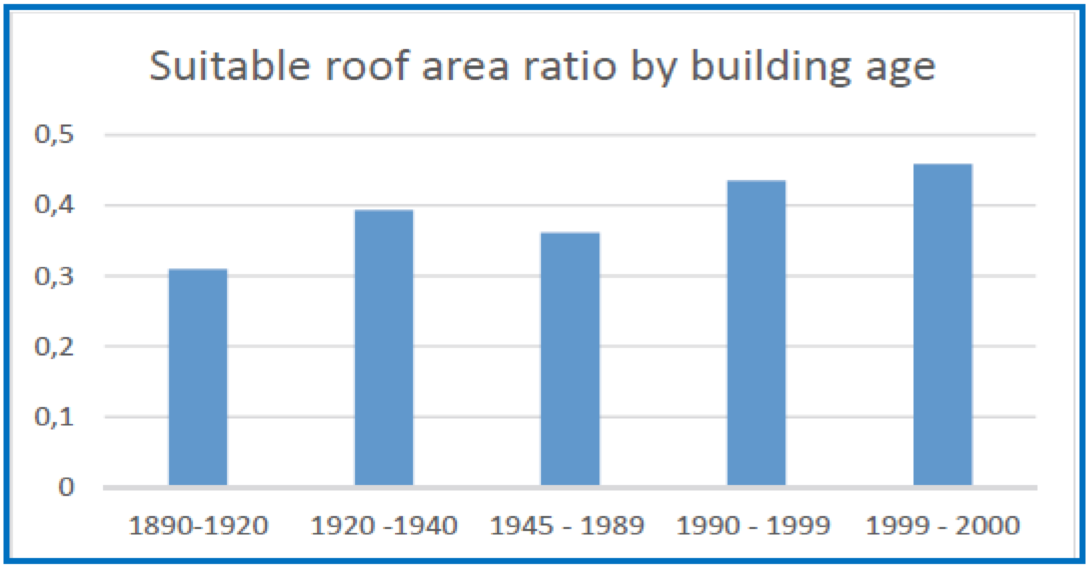


Figure 51: Suitable roof area ratio by building age

As illustrated in Figure 52, the increasing suitable roof area ratio goes along with higher energy savings and carbon emission reductions for newer buildings. However, this does not change the fact the old buildings are remain so called hard to treat buildings. For the residential building stock of Hackbridge suburb, a coherence between building age and solar admittance can be examined.

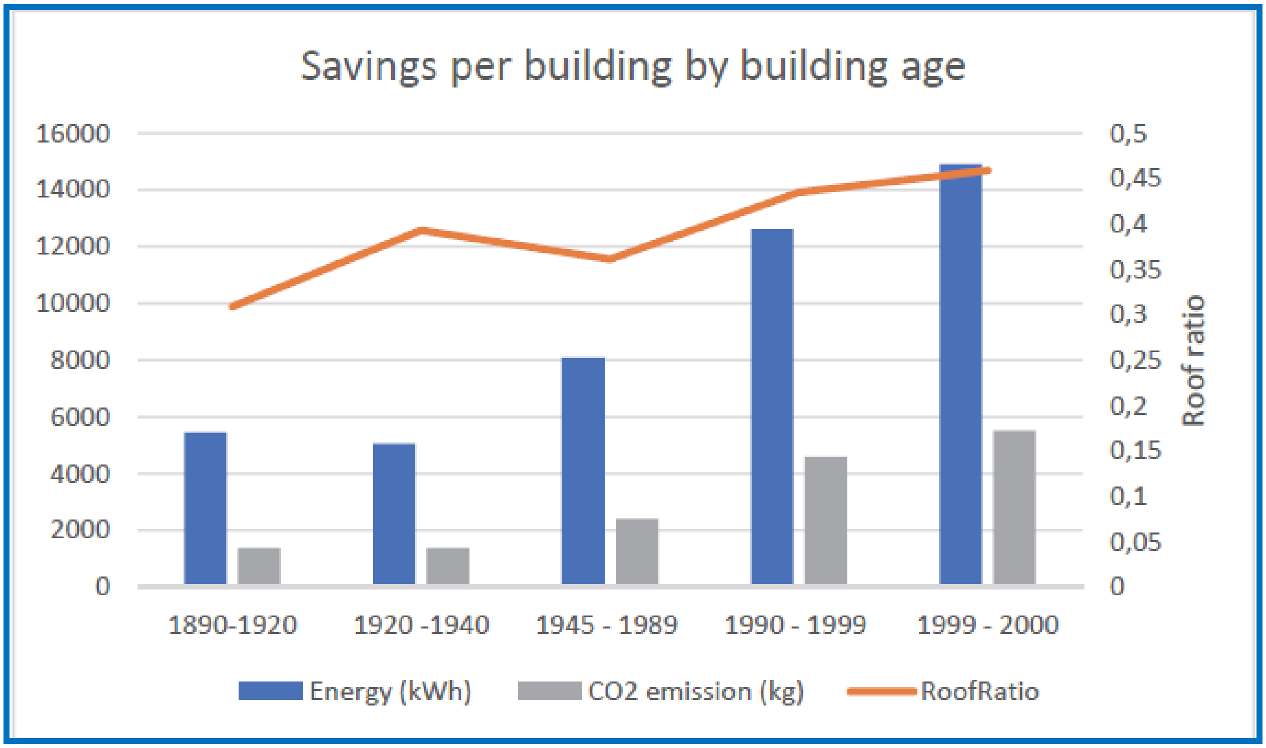


Figure 52: Suitable roof area ratio compared to building ages and the contribution of solar power

4.8 Building age

This section clarifies the energy savings accomplished through photovoltaics as shown in Table 11. Hence, the corresponding carbon emissions per household are compared to the building age based on the previous findings for this examination that newer buildings have an improved solar admittance. Likewise, previous studies by Deakin *et al.,* (2015) offered that newer buildings are generally more energy efficient than older ones. On the other hand, the CO_2 emission does not follow that fashion and stays roughly the same for varying building ages.

Table 11: Energy savings and carbon reductions by building age p.a.

Building Age	1890-1920	1920 -1940	1945 - 1989	1990 - 1999	1999 - 2000
Energy consumption [kWh]	12,188,230	12,708,626	10,407,728	8,459,635	5,725,379
Carbon emissions [kg.]	3,097,613	3,431,643	3,060,339	3,053,827	2,156,964
Energy Savings [kWh]	664,328	108,3457	1,002,685	782,177	491,667
Carbon reductions [kg]	168,963	293,996	297,098	284,488	181,851
Energy Savings per household [kWh]	1,632	2,267	1,778	1,501	1,358
Carbon Reductions					

Per household [kg]	415	615	527	546	502

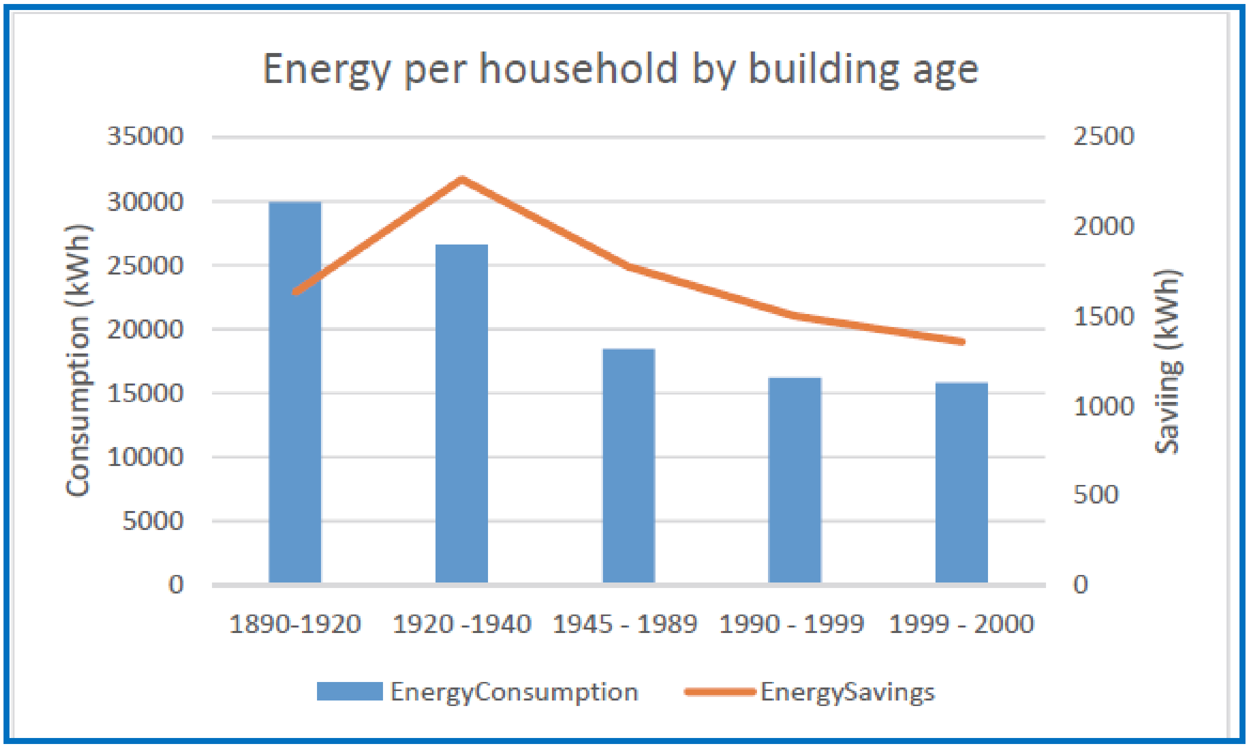


Figure 53: Present energy consumption and energy savings per household by building age

Consequently, Figure 53 associates the energy consumption per household to the energy savings per household for different building ages. Such analysis displays the decrease of energy consumption per household towards newer buildings. Since newer buildings have a better solar admittance, older buildings exhibit the higher energy saving per household. Buildings built in the 1930s have the highest saving per household. This is because most of them are semi-detached houses, while later built buildings often contain multiple properties and the generated solar energy per building is distributed to more households.

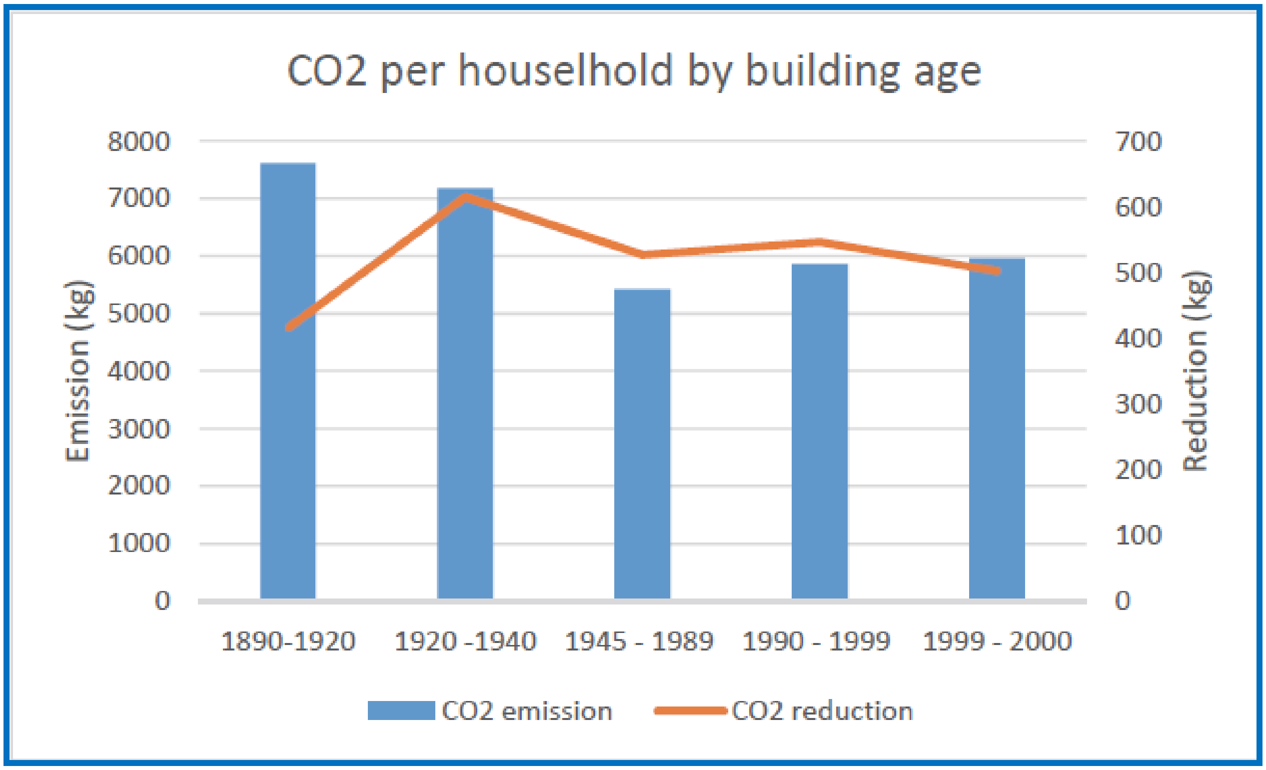


Figure 54: Present CO_2 emissions and CO_2 reduction per household by building age

As illustrated in Figure 54, this situation also effects the carbon reduction per household. As a result of the calculated energy savings and carbon emissions per household, it can be indicated that buildings aged between 1890 and 1920 perform worst. They have the lowest CO_2 reduction per household despite higher energy savings than buildings aged post-1990. It should be clarified that this comparison only respects the influence of solar energy produced from photovoltaics per household by building age. Albeit 1930s semi-detached houses have the highest savings per household, however concerning energy consumption, 1930s semi-detached buildings perform poorly compared to larger building blocks with many flats.

4.9 Area-based Analysis

As an area-based analysis, this assessment of consumption and emission by structure of tenure draws upon data profiled from LSOA's 1 and 5. The reasons this study also focuses attention on these areas are:

i. LSOAs 1 and 5 provide measures of the most and least deprived areas within the urban regeneration footprint. Here, Area 1 is the most deprived with a ranking within the 21% most deprived areas in England, whereas Area 5 has a much lower ranking within the 29% least deprived;
ii. while roughly similar in terms of building type, age, and levels of consumption and emission, the social-rented sector is prevalent in Area 1, whereas in Area 5 the owner-occupied and private-rented sector are the main sectors of the housing market;
iii. such an area-based analysis provides evidence to suggest which type of tenure consumes the least or most amount of energy and relationship this, in turn, has to the levels of emissions from the residential property in question.

Subsequently, previous analytical approach associated both LSOAs to ascertain which kind of tenure performs best or worst in terms of energy consumption and carbon emissions. This evaluation is reiterated to associate areas with different social-demographic structures in terms of energy output of photovoltaics and carbon reductions.

Table 12: Energy savings and carbon reductions for LSOA 1 and LSOA 5 p.a.

	LSOA 1	**LSOA 5**
Energy consumption [kWh]	6,733,319	8,079,019

Carbon emissions [kg]	1,904,109	2,176,338
Energy savings [kWh]	533,545	535,859
Carbon reductions [kg]	153,810	150,028
Energy savings per household [kWh]	1,809	1,696
Carbon reductions per household [kg]	521	475
Energy savings per capita [kWh]	770	693
Carbon reductions per capita [kg]	222	194

The energy savings and carbon reductions for LSOA 1 and LSOA 5 is presented in Table 12. Hence, current energy consumption and carbon emissions to the savings with photovoltaics for both LSOAs are compared as illustrated in Figure 55 and 56. The energy consumption per capita is higher in LSOA 5. Similarly, the CO_2 emissions per capita. On the other hand, the energy saving and the CO_2 reduction per capita with photovoltaics is higher for LSOA 1. This is interesting in the respect, that it is unlikely, that socially deprived people would install solar panels as it is a very cost expensive purchase.

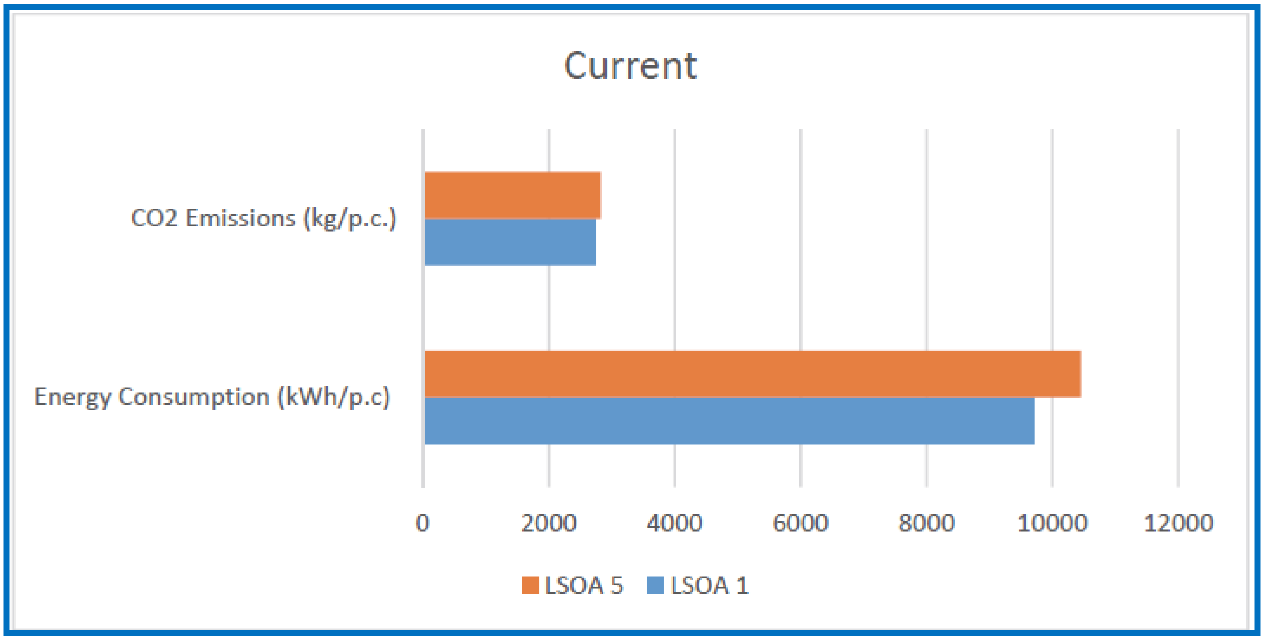


Figure 55: Current energy consumption and CO_2 emissions per capita

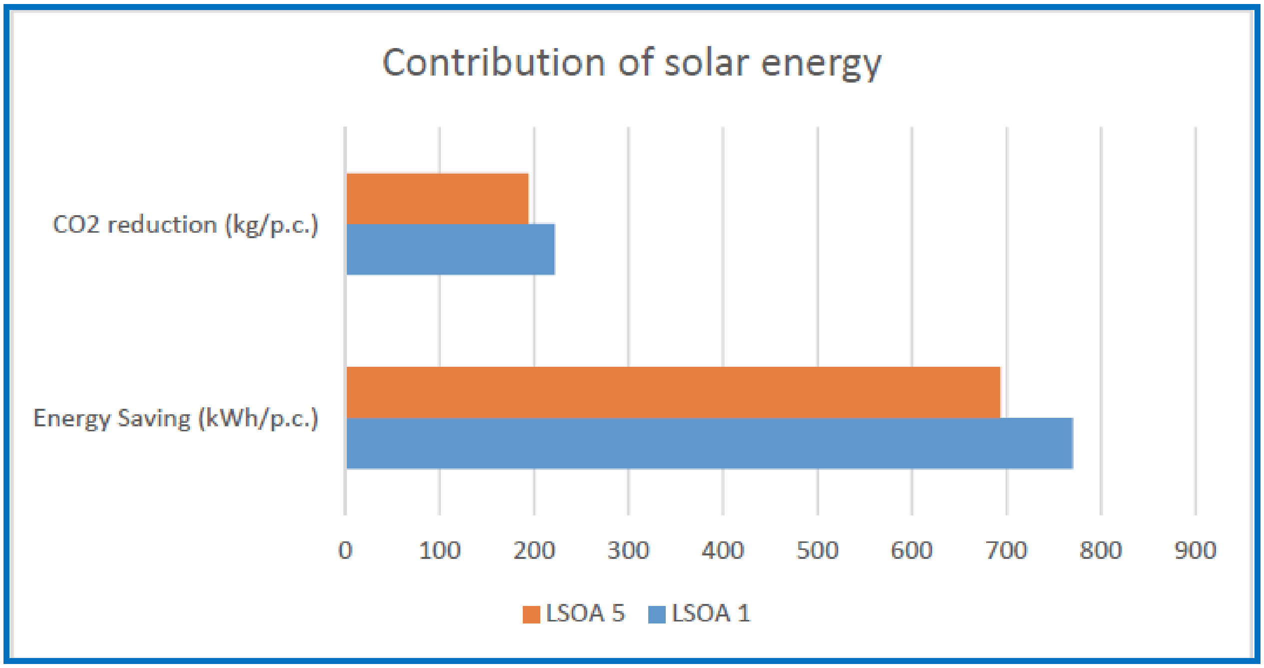


Figure 56: Energy savings and CO_2 reduction per capita

Figure 57 illustrates that by way of associating the suitable roof area per capita and the suitable roof ratio for both LSOAs uncovers the differences between the values. LSOA 1 has a better solar admittance, in terms of a higher suitable roof area ratio and a higher suitable roof area per capita. Although, the roof area p.c. can be examined to calculate the share of a single individual on the costs of a joint photovoltaic system. Thusly, this measurement could be examined particularly in deprived areas where it is unlikely that individuals would spend money for photovoltaics. The higher suitable roof area p.c. for LSOA 1 clarifies the margin in energy savings and carbon reductions.

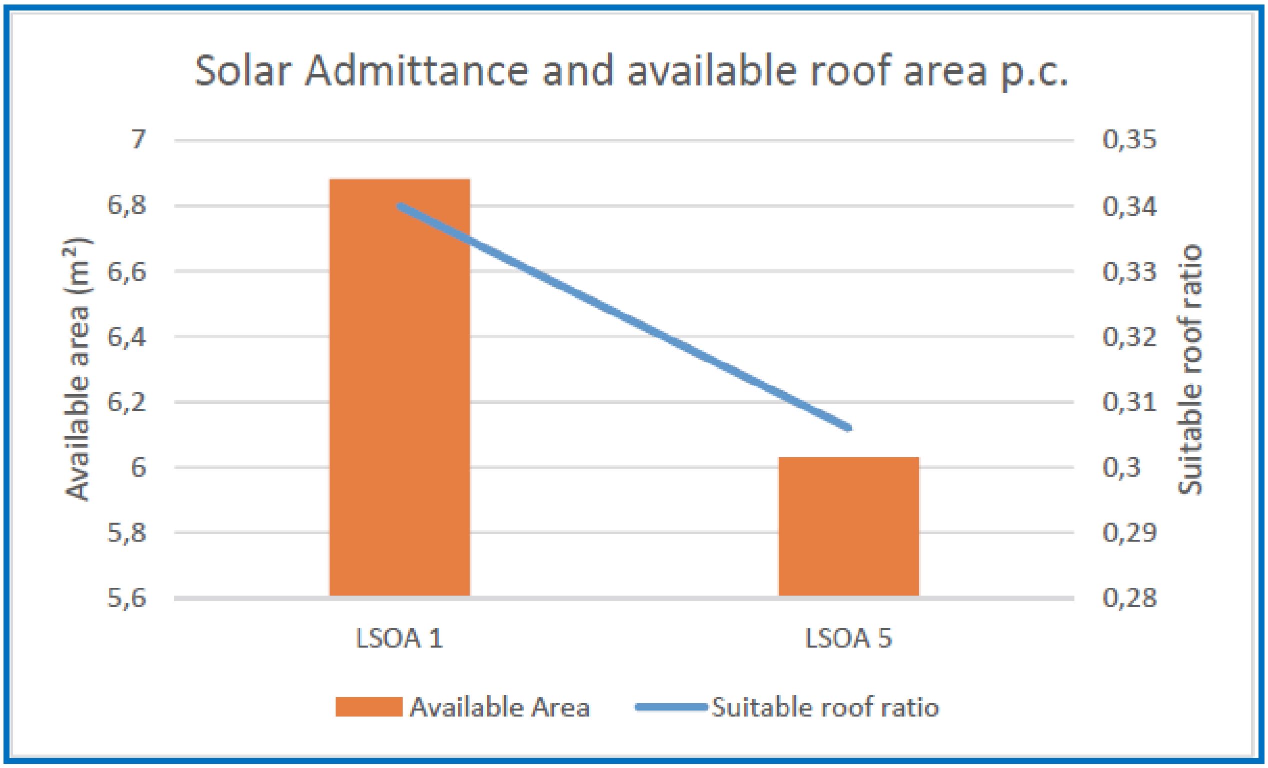


Figure 57: Available roof area per capita and suitable roof ratio per LSOA

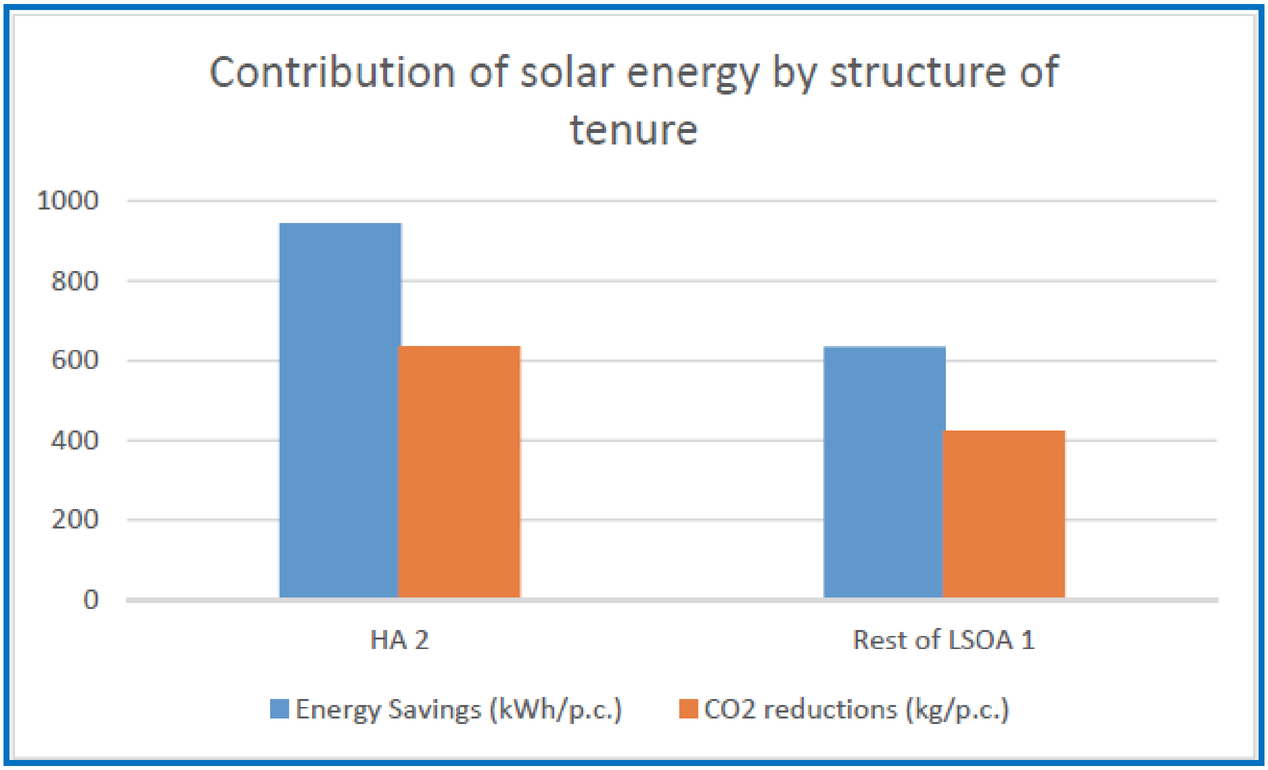


Figure 58: Contribution of solar energy by structure of tenure

In the drive towards a sustainable energy efficient-low carbon zone to include occupational behavior, LSOA 1 is further segmented across the structure of tenure into the social-rented sector and the private-rented and owner-occupied sector. The segmentation is implemented by areas of similar housing (HAs). LSOA 1 contains three different areas of similar housing, whereby HA 2 is predominantly social rented. As illustrated in Figure 58, HA 2 is compared to HA 1 and HA 3, where properties are mainly private-rented or owner-occupied. The analysis demonstrates that in the social-rented sector of HA 2 more energy could be saved per capita than in the rest of LSOA 1, and consequently the reduction of carbon emissions per capita are higher as well.

Chapter Five

5.0 Conclusion

Buildings are major contributors to energy consumption and carbon emissions, yet unlike other industries/ technologies, workable solutions are available to achieve a significant reduction. This study aims to unfold the significance of renewable energy source in the retrofit and uncover the key contribution it makes to the levels of energy consumption and carbon emission. For this goal is attributed to the sustainability of Hackbridge's suburb and the impact it makes to tackle global warming as part of a climate change adaptation strategy. This means that renewables are the key components of the mass retrofit study as it promotes to reduce levels of energy consumption and carbon emission, vis-à-vis establish energy efficient-low carbon zones as an exercise in the development of sustainable suburbs that not only tackles global warming but combats climate change.

Objective 1: To review the literature on mass retrofits

As the urban morphology Ratti *et al.,* (2005) advances offers insight into the levels of energy consumption and rates of carbon emission, the DEM it is founded on is too course, lacking the surface, shape and form to substantiate the factor values the model attributes to the four key components of their performance. This in turn means the claims made by Ratti *et al.,* (2005) that modifications to the urban design and layout of buildings can lower energy consumption by as much as 30% and carbon emissions by 50% remain unsubstantiated, as too are the possibility of further reductions contributing to climate change adaptation strategies. As studies by Deakin *et al.,* (2012a, 2012b) also highlight, this means existing retrofit proposal have no morphological basis, geometry or physics to instruct Ratti *et al.,* (2005); Hetherington *et al.,* (2010) as programmes of transformation, targeting energy consumption, carbon emissions and combatting global warming as part of a climate change adaptation. This exposes a serious fault line in urban morphology and need to ground retrofit proposals in the case-based reasoning of such applications by stepping back from the model as a means to found it on a more stable and secure procedural modelling approach. Deakin *et al.,* (2012a, 2012b, 2014) suggest this is best achieved by grounding the retrofit in a case-based analysis of retrofits and building the DEM to meet the requirements. While this is what Deakin *et al.,* (2014) go on to do, the argument they make as to the "grounds for", "context of" the buildings for the retrofit, term to see the key component analysis of the factor values in a too technical specification of the terms of reference. For what is key to the mass retrofitting of an energy efficient-low carbon zone as a sustainable suburb is not so much the levels of energy consumption and carbon emission, but the renewables it is based on and procedural modelling approach this founds. This is because without this key component it would not be possible to suggest whether-or-not the retrofit; levels of energy consumption and carbon emission are elevating this suburb into a sustainable problem.

Objective 2: To use the findings of this literature review as a basis to augment and supplement the procedural modelling currently available to render roof structures a principal component of mass retrofit proposals.

For a significant method to be established, this thesis substantiated the contribution of renewable energy source to energy consumption and carbon emissions of buildings by drawing upon an existing case study of sustainable urban development in terms of urban morphology of Hackbridge suburb. A much-detailed way of enhancing Level of Detail (LoD) 1 into Level of Detail (LoD) 2 is created that apprehends the roof structures of the vital components of this urban morphology, which only building footprints and building height values are required as input data. For the workflow offered to construct the model intentionally refrains from using cost expensive, readily modified 3D information, gathered from geodetic measurements. This consequently enables the potential ways of reviewing and modelling solar energy for Hackbridge suburb and it technically illustrate the option of accurately modelling spatial and temporal variation flows over urban models. In addition, the advanced analytic capabilities in both research fields enabled a combination of these disciplines in-order to gain a better understanding of building energy performance. This allowed the contribution of solar energy that render roof structures a principal element of energy consumption and the carbon emissions critically evaluated. More importantly, this procedural modelling enabled to build 3D city models of Hackbridge districts without the need for cost expensive 3D data gathered with geodetic measurements, by way of drawing on 3D information in the input features attributes, which is in turn acquired from open data sources. Hence, the OSMM Height Attribute data employed as alternative shows similar characteristics. The accuracy of the input data and the influence of inaccuracies with regard to modelling solar radiation estimates remains estimated and appraised respectively. In the drive towards the development of energy efficient-low carbon zones, this examination unfolds that using a procedural modelling approach provides good results.

Objective 3: To calculate the solar-power these roof structures generate as sources of renewable energy, by supplementing building footprint data with height and slope information.

Subsequently, the progressed model using procedural modelling approach suggested that the building footprints and heights of this suburb allows to supplements the data with height information needed to calculate solar radiation estimates over Hackbridge urban environment using a raster based and a vector based modelling approach. However, the comparison of the outcomes revealed that both provide similar results and can exhibit the urban structure and consider the effects of surrounding urban geometry on incoming solar radiation. Thusly, the radiation received on rooftops based on the yearly radiation values for roof surfaces and the energy output for photovoltaics is calculated. Similarly, the roofs classified as suitable and non-suitable depends upon the received solar radiation and the available area.

Objective 4: To reveal what these renewable energies contribute to the development of energy-efficient low carbon zones as sustainable suburbs.

Renewable energy sources clearly contributed to the economic, social and environmental energy sustainability of Hackbridge venture. At a result, they reduce carbon emissions, energy consumption and create local socioeconomic development opportunities:

- *Environmental* - Reduction of local and global pollution (among them, emissions of greenhouse gases, and climate change), lower exploitation of the natural resources in the territory and maintenance of the resilience (ability to adapt to change), integrity and stability of the ecosystem.
- *Economic* - Increase of regional per capita income, improvement in the standard of living of the local population of Hackbridge, reduction of energy dependence and increase in the diversification of energy supply.
- *Social* – The development of energy-efficient low carbon zones as sustainable suburbs is achieved with the sustainability of social and cultural systems, which includes the achievement of peace and social cohesion, stability, social participation, respect for cultural identity and institutional development. Reducing unemployment and improving the quality of jobs (more permanent jobs), increasing regional cohesion and reducing poverty levels are key aspect renewables contribute at local level to achieve social sustainability.

5.1 Limitations and Further Research

This thesis demonstrated the influence of urban morphology on building energy consumption and illustrated a connection between urban morphology, solar radiation and renewable energies. Hence, different case studies were reviewed. Ratti *et al.,* (2005) and Salat (2009) examined DEM's to explore the effects of urban morphology on energy consumption. However, the DEM approach shows diagnostic limitations, as a DEM can only represent one component, and therefore different factors on energy performance cannot be coupled to consider effects they have on each other. This study overcome this limitation by developing procedural modelling approach and a 3D model of urban morphology, which allows to integrate more factors into the analysis by enriching the 3D model with attributes. Accordingly, they can be regarded alongside each other. This methodological approach allows to determine the contribution of solar energy to building energy consumption.

However, after introducing procedural modelling rules for combinations of shapes and more general volumetric shapes such as roofs, the strict hierarchy of the split-grammar can no longer be enforced. The idea of split rules is a very suitable primitive to generate facade details, but this study did not find it suitable for many forms of mass modelling of Hackbride rooftops. This study made use of the control grammar to generate procedural variations together with simple stochastic rules. The models offered by this study underpins context sensitive shape rules, together with the interplay of one, two, and three-dimensional modelling are an elegant and efficient solution to a challenging problem. Besides this major conceptual contribution, this study also address the application related details, such as the definition of the most important shape rules, the concise notation, and modelling examples detailing various modelling strategies.

Following the discoveries of this thesis, the knowledge acquired based upon GIS modelling techniques, the powerful analytic capabilities of a procedural modelling 3D urban model in terms of assessing buildings energy performance and ways it is associated to sustainable urban developments can further remain exploited.

- For the Hackbridge suburb, different suggestion demonstrates that trees, industrial and public buildings can remain moulded and integrated within the examination.
- The current model could remain examined to calculate the contribution of wind as a renewable energy and to capture solar radiation incident at all building surfaces.
- Further study could also enhance the model to a higher LoD (Level of Detail). In LoD 3, passive solar gains could remain captured and in LoD 4, internal systems could be included in the analysis. This would provide an even better understanding of carbon emissions and energy performance of buildings associated with the influence of urban morphology. However, one main challenge for this future work is to develop higher levels-of-detail techniques for Hackbridge city models as this study currently do not optimize for consistent topology, existing algorithms would fail.

5.2 Contribution to Knowledge

This thesis uncovers the contribution of renewable energy source in the retrofit and the significant contribution it makes to the retrofits, levels of energy consumption and attributed to the sustainability of the suburb and contribution this in turn makes to tackle global warming as part of a climate change adaptation strategy. It demonstrates that for this thesis, renewables are the key components of the mass retrofit study as it promotes to reduce levels of energy consumption and carbon emission, vis-à-vis establish energy efficient-low carbon zones as an exercise in the development of sustainable suburbs. It clearly reveals the key green values it makes to the levels of energy consumption, rates of carbon emission and sets a standard of "sustainable suburbs" that not only tackles global warming but combats climate change. This study:

- unfolds technical excellence to ensure the successful urban morphology approach to the fabric of structures and districts of Hackbridge into an energy efficient low carbon zone.
- delivers outstanding innovative standards to the current state-of-the-art that likewise underlie the typich and which support the behaviour of occupiers in terms of what they not only add to the environmental sustainability of such developments, but in turn contribute to the performance the emerging post-carbon economy.
- makes a significant contribution to sustainable development (reduction of carbon footprints) which is in turn systematically integrated into a set of actions and programme of intervention whose assessments work to transform the structures and districts under review into an energy efficient-low carbon zone.
- brings environmental, economic and social benefits to Hackbridge district that sets the standards of a "sustainable suburb": an energy efficient low carbon zone.
- supports and promotes clean, secure and economically viable renewable energy model by mitigating the worst effects of climate change as designated in the newly released ISO white paper dated 3rd June 2015 by ISO New England on

which circles as actions able to meet the standards of environmental sustainability sets out in the 2008 UK Climate Bill.

This thesis subsequently proves that the best way to implement procedural modelling technique is by using a key-renewable-based model of urban morphology designed and examined for a sustainable energy efficient low carbon zone. It theoretically opens more possibilities to examine different attributes of renewable-based models associated with the inhabitant of buildings while reducing the rate of energy consumption and carbon emission as part of climate change adaptation approaches. This shall assist the new approach of Deakin *et al.,* (2015) not only with a better morphological model, but also with a more applicable way to analyze diverse attributes of renewable-based models associated with the use of procedural modelling system.

To unveil the degree to which the contribution of solar energy greens the urban morphology of energy efficient-low carbon zones: connections between the derived values, morphological parameters (surface-to-volume-ratio, building age, suitable roof area ratio) and energy consumption/carbon emissions are presented. By comparing the contribution of solar energy to different structures of tenure in this thesis: it demonstrated how the unique model of urban morphology allows to consider socio-demographic factors, vis-à-vis to the major impacts it makes in the development of energy efficient-low carbon zones as sustainable suburbs, that is able to tackle global warming and combat climate change as part of an adaptation strategy.

References

Adams, D. (2009). *Zero Carbon Homes Programme Delivery Timeline*, Zero Carbon Hub.

Adv (2013), “Modellierungsbeispiele_für_3D-Gebäudemodelle. Version 1.0”. Available at: http://www.adv-online.de/AdV-Produkte/Standards-und Produktblaetter/Beispielsammlungen/ (Accessed 28 November, 2015).

Applegate, C. S., Laycock, S. D., and Day, A. (2012). A sketch-based system for highway design with user-specified regions of influence. Comp. & Graph. 36, 6, 685–695.

Atkinson, C. (2009). *Sustainability in the built environment: an introduction to its definition and measurement*, Bracknell England: IHS BRE Press.

Badescu, V. (2008). Modeling Solar Radiation at the Earth's Surface: Recent Advances, Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg.

Bae, S., Balakrishnan, R., and Singh, K. 2008. I love sketch: as-natural-as-possible sketching system for creating 3d curve models. In User Interface Software and Technology.

Bing Maps. (2015). www.bing.com

Bioregional Consulting (2008). “Energy Options Appraisal for Domestic Buildings in Hackbridge”.

BioRegional Development Group (2011), “Hackbridge - A Zero Carbon Suburb. An area based strategy for zero carbon buildings”, available at: http://www.bioregional.com/wp-content/uploads/2015/03/Hackbridge-

%E2%80%93-a-Zero-Carbon-Suburb-An-area-based-strategy-for-zero-carbon-buildings_v2.pdf.

Bourdic, L., & Salat, S. (2012). Building energy models and assessment systems at the district and city scales: A review. Building Research and Information, 40(4), 518–526.

Bourdic, L., Salat, S., & Nowacki, C. (2012). Assessing cities: A new system of cross-scale spatial indicators. Building Research and Information, 40(5), 592–605.

Carneiro, C., Morello, E. and Desthieux, G. (2009), "Assessment of Solar Irradiance on the Urban Fabric for the Production of Renewable Energy using LIDAR Data and Image Processing Techniques", in Sester, M., Bernard, L. and Paelke, V. (Eds.), *Advances in GIScience: Proceedings of the 12th AGILE Conference*, *Lecture Notes in Geoinformation and Cartography*, Springer-Verlag, Berlin Heidelberg, pp. 83–112.

Carneiro, C., Morello, E. and Desthieux, G. (2009). "Assessment of Solar Irradiance on the Urban Fabric for the Production of Renewable Energy using LIDAR Data and Image Processing Techniques", in Sester, M., Bernard, L. and Paelke, V. (Eds.), *Advances in GIScience: Proceedings of the 12th AGILE Conference*, *Lecture Notes in Geoinformation and Cartography*, Springer-Verlag, Berlin Heidelberg, pp. 83–112.

Chen, G., Esch, G., Wonka, P., M¨Uller, P., and Zhang, E. (2008a). Interactive procedural street modeling. ACM Trans. Graph. 27, 3, 103:1–103:10.

Chow, A., Fung, A. and Li, S. (2014), "GIS Modeling of Solar Neighborhood Potential at a Fine Spatiotemporal Resolution", *Buildings*, Vol. 4 No. 2, pp. 195–206.

City of Osnabrück (2015). "Stadt Osnabrück: Solarpotential Osnabrück", available at: http://www.osnabrueck.de/fileadmin/user_upload/umwelt/Solardaecher_Solardachpotential_Photovoltaik_Berechnung.pdf

Climate Change Act of 2008. (2008). Great Britain.

Curwell, S., Deakin, M., & Symes, M. (Eds.). (2005). Sustainable urban development volume 1: The framework, protocols and environmental assessment methods. Oxon: E&FN Spons.

Deakin, M. (2004). The NAR model. In M. Deakin (Ed.), Property management: Corporate strategies, financial instruments and the urban environment. Aldershot: Ashgate Press.

Deakin, M. (2008a). Definitional components of sustainable communities: The net effect of a realignment and cross-sectional representation. International Journal of Design Principles and Practices, 3(1), 183–196.

Deakin, M. (2008b). The NAR model of land use and building assessment. In: Deakin, M., Vrekeer, R., Curwell, S. (Eds.), Sustainable Urban Development Volume 3: the Toolkit for Assessment. Routledge, Oxon.

Deakin, M. (2008c). Definitional components of sustainable communities: the net effect of a realignment and cross-sectional representation. International Journal of Design Principles and Practices 3 (1), 183–196.

Deakin, M. (2009). A Community-based approach to sustainable urban regeneration. Journal of Urban Technology 16 (1), 91–110.

Deakin, M. (2009c). The search for sustainable communities. In R. Vrekeer, M. Deakin & S. Curwell (Eds.), Sustainable urban development volume 3: The toolkit for assessment. Oxon: Routledge.

Deakin, M. (2011). Learning from what works in sustainable community development. Sustainable Cities and Society, 1(4), 244 251.

Deakin, M., & Allwinkle, S. (2007). Urban regeneration and sustainable communities: The role networks, innovation and creativity in building successful partnerships. Journal of Urban Technology, 14(1), 77–91.

Deakin, M., & Allwinkle, S. (2008). A community-based approach to sustainable urban regeneration: The LUDA project. International Journal of Inter-disciplinary Social Sciences, 3(5), 181–191.

Deakin, M., Campbell, F. and Reid, A. (2012a) “The mass-retrofitting of an energy efficient low-carbon zone: baselining the urban regeneration strategy, vision, master-plan and redevelopment scheme.” *Energy Policy* 45: 187-200*.*

Deakin, M., Campbell, F. and Reid, A. (2012b). “The mass-retrofitting of an energy efficient low carbon dioxide zone” *Energy* 165 (4): 197-208.

Deakin, M., Curwell, S., & Lombardi, P. (2002). Sustainable urban development: The framework and directory of assessment methods. Journal of Environmental Assessment, Management and Policy, 4(2), 171–198.

Deakin, M., Mitchell, G., Nijkamp, P., & Vrekeer, R. (Eds.). (2007). Sustainable urban development volume 2: The environmental assessment methods, Oxon: E&FN Spons.

Deakin, M., Reid, A., & Campbell, F. (2013). Demonstrating how urban morphology matters: Reaching beyond the geometry of the building design, construction systems and occupational behaviours and towards broader context-specific transformations. Environmental Management and Sustainable Development, 2(2), 101–121.

Deakin, M., Reid, A., & Campbell, F. (2014). Demonstrating how urban morphology matters by reaching towards broader context-specific transactions. The International Journal of Architectonic, Spatial and Environmental Design, 7(3), 57–74.

Deakin, M., Reid, A., Campbell, F. and Orsinger, J. (2015). *The mass-retrofitting of an energy efficient - low carbon zone,* Springer, New York.

DECC (2012). Science and innovation strategy. Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48335/5107-decc-science-innovation-strategy-2012.pdf

DECC (2013). Electricity Generation Costs. Available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223940/DECC_Electricity_Generation_Costs_for_publication_-_24_07_13.pdf

Department for Communities and Local Government. (2007). “Building a Greener Future: policy statement,”

Derzapf E., Ganster B., Guthe M., and Klein R., (2011). River Networks for Instant Procedural Planets. In: Computer Graphics Forum (Sept. 2011), 30:7 (2031-2040). Volume 30 (2011), Number 7

Dobos, A.P. (2014). “PVWatts Version 5 Manual”, available at: https://sam.nrel.gov/sites/sam.nrel.gov/files/content/documents/pdf/pvwattsv5-draft-march-14-2014.pdf

Dubayah, R. and Rich, P. M. (1995). “Topographic solar radiation models for GIS”, *International journal of geographical information systems*, Vol. 9 No. 4, pp. 405– 419.

Edwards, B. (2009). *Rough guide to sustainability*, London: RIBA.

Elkington, J. (1998). *Cannibals with forks: the triple bottom line of 21st century business*, Gabriola Island BC; Stony Creek CT: New Society Publishers.

Emilien, A., Vimont, U., Cani, M.-P., Poulin, P., and Benes, B. (2015). World brush: Interactive example-based synthesis of procedural virtual worlds. ACM Trans. Graph. 34, 4, 106:1–106:11.

Esri (2014), “ArcGIS Help 10.2 - Area Solar Radiation”, available at: http://resources.arcgis.com/en/help/main/10.2/index.html#//009z000000t5000000 (Accessed 31 May 2015).

Esri R&D Center (2015), “CityEngine Help. Version 2015.0”, available at: http://cehelp.esri.com/help/index.jsp?topic=/com.procedural.cityengine.help/html/toc.html (Accessed 31 May 2015).

Forberg, A. (2007). Generalization of 3D building data based on a scale-space approach. ISPRS Journal of Photogrammetry & Remote Sensing 62 (2007) 104–111

Fu, P. and Rich, P.M. (1999), "Design and Implementation of the Solar Analyst: An ArcView Extension for Modeling Solar Radiation at Landscape Scales", *Proceedings of the Nineteenth Annual ESRI User Conference, San Diego*.

Ganster B. and Klein R., (2007). An Integrated Framework for Procedural Modelling. *In proceedings of Spring Conference on Computer Graphics 2007 (SCCG 2007), pages 150-157, Comenius University, Bratislava, Apr. 2007*

Grondzik, W.T. (2010). *Mechanical and electrical equipment for buildings,* 11th ed., Wiley, Hoboken, N.J.

Hamza, N. and Horne, M. (2007). "Building Information Modelling: Empowering Energy Conscious Design," *3rd Int'l ASCAAD Conference on Em'body'ing Virtual Architecture*, Alexandria, Egypt.

Hetherington, R., Laney, R. and Peake, S. (2010). Zero and low carbon buildings: A driver for change in working practices and the use of computer modelling and visualization. In: 14th International Conference on Information Visualisation, 27-29 July 2010, London South Bank University London, UK.

Hofierka, J. and Zlocha, M. (2012). "A New 3-D Solar Radiation Model for 3-D City Models", *Transactions in GIS*, Vol. 16 No. 5, pp. 681–690.

Ijiri, T., Owada, S., and Igarashi, T. (2006). The sketch l-system: Global control of tree modelling using free-form strokes. In Smart Graphics, Springer, 138–146.

Jahn, U., Mayer, D., Heidenreich, M., Dahl, R., Castello, S., Clavadetscher, L., Frölich, A., Grimmig, B., Nasse, W., Sakuta, K., Sugiara, T., van der Borg, N. and van Otterdijk, K. (2000). "International Energy Agency PVPS Task 2: Analysis of the operational performance of the IEA database PV systems", *16th European Photovoltaic Solar Energy Conference and Exhibition*.

Kolbe, T. H. (2008). Representing and Exchanging 3D City Models with CityGML, In: Proceedings of the 3rd International Workshop on 3D Geo-Information, Seoul, Korea.

Lipp, M., Wonka, P., and Wimmer, M. (2008). Interactive visual editing of grammars for procedural architecture. ACM Trans. Graph. 27, 3, 102:1–102:10.

Lipson, H., and Shpitalni, M. (1996). Optimization-based reconstruction of a 3d object from a single freehand line drawing. Computer-Aided Design 28, 651–663.

Lipson, H., And Shpitalni, M. (2000). Conceptual design and analysis by sketching. Artif. Intell. Eng. Des. Anal. Manuf. 14, 5, 391–401.

London Borough of Sutton (2008a). Draft Development Plan Document: Core Planning Strategy. Available at http://www.sutton.gov.uk/CHttpHandler.ashx?id=3429&p=0.

London Borough of Sutton (2008b). Energy Options Appraisal for Domestic Buildings in Hackbridge. Produced by Parity Projects. See http://www.sutton.gov.uk/ CHttpHandler.ashx?id¼5173&p¼0 [Accessed 03/05/2015].

March, L. (1972). Elementary models of built forms. In L. Martin & L. March (Eds.): Urban space and structures. Cambridge: Cambridge University Press.

Matchatile (2015), “Roof pitch calculator”. Available at: http://www.matchatile.co.uk/roof-tile-calculator/roof-pitch-calculator.html (Accessed 3 June 2015).

Meng, L., Forberg, A. (2007). 3D Building Generalisation. In: Mackaness, W., Ruas, A. and Sarjakoski, T. (Eds): Challenges in the Portrayal of Geographic Information: Issues of Generalisation and Multi Scale Representation. Chapter 11, Elsevier Science Ltd.

Morello, E. and Ratti, C. (2009). “Sunscapes. ‘Solar envelopes’ and the analysis of urban DEMs”, *Computers, Environment and Urban Systems*, Vol. 33 No. 1, pp. 26–34.

Muller, P., Wonka, P., Haegler, S., Ulmer, A., and Van Gool, L. (2006). Procedural modeling of buildings. ACM Trans. Graph. 25, 3, 614–623.

Muneer, T. (2004). *Solar Radiation and Daylight Models: For the Energy Efficient Design of Buildings,* 2. Aufl., Elsevier professional, Oxford. Badescu, V. (Ed.) (2008), *Modeling Solar Radiation at the Earth's Surface: Recent Advances*, Springer-Verlag Berlin Heidelberg, Berlin, and Heidelberg.

NAEI (2015). Air Quality Pollutant Inventories for England, Scotland, Wales and Northern Ireland: 1990-2013. A report of the National Atmospheric Emissions Inventory, September 2015. Available at http://uk-air.defra.gov.uk/assets/documents/reports/cat07/1509110857_DA_AQPI_1990-2013_Report_Issue1.pdf

Office for National Statistics (2001) Census: Digitised Boundary Data (England and Wales). ESRC/JISC Census Programme, Census Geography Data Unit (UKBORDERS), Census Dissemination Unit, Mimas (University of Manchester).

Olsen, L., Samavati, F. F., Sousa, M. C., and Jorge, J. A. (2009). Sketch-based modeling: A survey. Comp. & Graph. 33, 1, 85–103.

One Planet Sutton (2014), “Progress Report”, available at: www.sutton.gov.uk/oneplanet.

Open Geospatial Consortium, I. (2006), “Candidate OpenGIS® CityGML Implementation Specification. City Geography Markup Language”.

Ordnance Survey (2014), “OS MasterMap Topography Layer user guide and technical specification. v1.12” Available at: http://www.ordnancesurvey.co.uk/docs/user-guides/os-mastermap-topographylayer-user-guide.pdf (Accessed 17 December, 2015).

Owens, S. (1986). Energy, planning and urban form. London: Pion Limited.

Pfidwirny, M. (2006). *Fundamentals of Physical Geography, 2nd Edition: The Solar Source of the Earth's Energy*.

PVGIS © European Communities (2012), "Photovoltaic Geographical Information System", available at: http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=europe

Ratti, C., Baker, N. and Steemers, K. (2005). "Energy consumption and urban texture." *Energy and Buildings* 37 (7): 762-776.

Richard P. (2016). Retrofitting Existing Buildings to Improve Sustainability and Energy Performance: Sustainability and Energy-Efficiency Strategies. National Institute of Building Sciences.

Ritchie, D., Mildenhall, B., Goodman, N. D., And Hanrahan, P. (2015). Controlling procedural modeling programs with stochastically-ordered sequential monte carlo. ACM Trans. Graph. 34, 4, 105:1–105:11.

Ruiz-Arias, J.A., Tovar-Pescador, J., Pozo-Vázquez, D. and Alsamamra, H. (2009). "A comparative analysis of DEM-based models to estimate the solar radiation in mountainous terrain", *International Journal of Geographical Information Science*, Vol. 23 No. 8, pp. 1049–1076.

Salat, S. (2009). Energy loads, CO2 emissions and building stocks: Morphologies, typologies, energy systems and behaviour. Building Research and Information, 37, 598–609.

Salat, S. (2011). Cities and forms. Paris: CSTB.

Salat, S. and Bourdic, L. (2011). Factor 10: multiplying by 10 resource productivity in the urban world, in Proceedings of the World Sustainable Building Conference – SB11, Helsinki, Finland.

Schmidt, R., Khan, A., Singh, K., and Kurtenbach, G. (2009). Analyticdrawingof3dscaffolds. ACM Trans. Graph. 28, 5, 149:1–149:10.

Smelik, R. M., Tutenel, T., Bidarra, R., and Benes, B. (2014). A survey on procedural modelling for virtual worlds. In Comp. Graph. Forum, vol. 33, 31–50.

Smelik, R., Tutenel, T., De Kraker, K. J., and Bidarra, R. (2010). Interactive creation of virtual worlds using procedural sketching. In Proceedings of euro graphics.

Stava, O., Pirk, S., Kratt, J., Chen, B., Mch, R., Deussen, O., and Benes, B. (2014). Inverse procedural modelling of trees. Comp. Graph. Forum 33, 6, 118–131.

Steadman, P., Bruhns, H., Holtier, S., & Gakovic, B. (2000). A classification of built form. Environment and Planning B: Planning and Design, 27, 73–91.

Steemers, K. (2003). Energy and the city: Density, buildings and transport. Energy and Buildings, 35(1), 3–14.

Sun, W., Nousiainen, T., Muinonen, K., Fu, Q., Loeb, N.G. and Videen, G. (2003). “Light scattering by Gaussian particles. A solution with finite-difference timedomain technique”, *Journal of Quantitative Spectroscopy and Radiative Transfer*, 79-80, pp. 1083–1090.

Suri, M. and Hofierka, J. (2004). “A New GIS-based Solar Radiation Model and Its Application to Photovoltaic Assessments”, *Transactions in GIS*, Vol. 8 No. 2, pp. 175–190.

Talton, J. O., Lou, Y., Lesser, S., Duke, J., Mˇech, R., and Koltun, V. (2011). Metropolis procedural modeling. ACM Trans. Graph. 30, 2, 11:1–11:14.

The English Indices of Deprivation (2007). Department of Communities and Local Government, London.

Tovar, J., Olmo F.J. and Alados-Arboledas, L. (1995). “Local-Scale Variability of Solar Radiation in a Mountainous Region”, *Journal of Applied Meteorology*, No. 34, pp. 2316–2322.

Vanegas, C. A., Garcia-Dorado, I., Aliaga, D. G., Benes, B., and Waddell, P. (2012). Inverse design of urban procedural models. ACM Trans. Graph. 31, 6, 168:1–168:11.

Wonka, P., Wimmer, M., Sillion, F., and Ribarsky, W. (2003). Instant architecture. ACM Trans. Graph. 22, 3, 669–677.

World Commission on Environment and Development. (1987). *Our common future*, Oxford; New York: Oxford University Press.

Xu, B., Chang, W., Sheffer, A., Bousseau, A., Mccrae, J., and Singh, K. (2014). True2form: 3d curve networks from 2d sketches via selective regularization. ACM Trans. on Graph. 33, 4, 131:1–131:13.

Yamaguchi, Y. (2003). Modeling approach to consider urban form for evaluation of city level energy management. Paper presented at the Meeting KCBS-BPS, Research Institute for Sustainability Science, Osaka University, Osaka, Japan.

Zeleznik, R. C., Herndon, K. P., And Hughes, J. F. (1996). Sketch: An interface for sketching 3d scenes. In Computer Graphics, Proceedings of Siggraph 1996, 163–170.

Zero Carbon Hub. (2015). "Consultation on Zero Carbon Non- Domestic Buildings" http://www.zerocarbonhub.org/events_details.aspx?even t=3 [Accessed March 31, 2015].

Zheng, Y., Liu, H., Dorsey, J., and Mitra, N. J. (2016). Smart canvas; context-inferred interpretation of sketches for preparatory design studies. Comp. Graph. Forum.