The Metabolism of Living Space: Allometric Scaling of Energy Use in UK Domestic Buildings

By

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Abstract

Understanding and reducing domestic energy usage is seen as key to achieving national greenhouse gas emission targets, as well ensuring sustainable consumption at a domestic level. Domestic buildings represent a well-defined unit of space with numerous, easily measurable characteristics. They can also be perceived as being the terminal, end-use elements of a global resource distribution network, as defined by Jarvis et al., (2015). Such networks have drawn comparisons to biological organisms in how they acquire, transform, use and dispose of resources from their surrounding environment through a metabolic system of processing. This thesis aims to more deeply understand interrelations between, people, energy and space at a domestic level, assessing the influence of building geometry and social practices on scaling relationships relating to domestic energy consumption. Scaling relationships relating to the physical building properties have been studied extensively, however none directly assess how total energy usage scales across the domestic building stock. Data is abstracted form the 2012 English Housing Survey (EHS) housing stock dataset, which contains physical and demographic data relating to ~14k randomly sampled households across England. Scaling relationships are established between household size and total energy usage, both across the entire housing stock and by selected building characteristics, revealing scaling effects pertaining to specific domestic properties. Across the entire housing stock, a scaling exponent of 0.8032 ± 0.013 is observed for the relationship between household total floor area and total energy consumption, indicating a decrease in energy use per unit space with increased household size. This result is set within a context of building geometric properties and theories of societal metabolism, drawing extensively on current literature and this researches own findings. Understanding the origins of such scaling could potentially hold important implications for how individuals perceive their energy consumption, both in relation to physical domestic buildings and wider society.

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Section 1: **Introduction**

General Introduction

It is widely recognised that global energy consumption continues to increase year on year, a trend that shows little sign of drastic change despite a conscious effort, particularly from more developed nations, to achieve this (International Energy Agency, 2013). There is also increasing evidence to suggest that this increase is intrinsically linked with economic growth, with an ever increasing demand for energy from a growing population (Stern, 2004), a link that appears practically unfeasible to sever given society's persistent reliance on material resources. Economic growth has been shown to be a "primary, perennial and bipartisan" multi-national goal (Czech and Daly, 2004), as all strive to achieve unprecedented levels of socio-economic development. This makes understanding the relationships that link growth in societal energy use to capital accumulation, human behaviours, and the use of space by society of ever increasing importance. As yet, there is no fundamental, comprehensive understanding of how these relationships manifest themselves, linking economic growth and the accumulation of capital, to the expansion and growth of society and the subsequent land use changes associated with this. The concepts outlined throughout this thesis aim to break new ground in this respect, helping to further understand the more fundamental ways in which society consumes energy. This is required not only to ensure the development of socio-economic sustainability, but also to ensure that issues relating to environmental protection and conservation are properly addressed.

In the United Kingdom (UK), energy used in domestic buildings currently accounts for around 30% of total consumption, having risen from around a quarter since 1970, representing a significant portion of an individual's energy portfolio, more than both industry and transport (Palmer and Cooper, 2013). Despite this, a significant increase in the number of UK households and a decrease in average household size mean that energy consumed per building has fallen over the same time frame. Domestic energy consumption is still, however, seen as a key sector for CO_2 emissions reduction, given the targets laid out in the 2008 Climate Change Act. The UK's stated objectives of a 34% reduction in Greenhouse Gas (GHG) emissions by 2020, along with an 80% reduction by 2050 (based on 1990 levels) will be difficult to achieve without further reductions in domestic consumption and improved energy use efficiency (LCICG, 2012). Understanding the nature by which domestic buildings, and their inhabitants, consume energy is, therefore, of both political and academic importance.

It can be argued that, as a unit of functional space, a domestic building is designed to facilitate the energy consumption of individuals within society, both directly through power and heating requirements, and indirectly allowing the use of products and resources acquired from wider society. However, just like consumer habits, our energy use expectations and ideals of thermal comfort have changed dramatically over recent decades, with buildings now required to allow use of an ever expanding range of consumer electricals and support central heating systems, with many properties built before the link between climate and energy use was established (Palmer and Cooper, 2013). It is expected that three-quarters of domestic buildings existing in the UK in 2050 have already been constructed (Morrell et al., 2010), making understanding how we inherently manipulate existing domestic space, as well as innovate in new design, critical to ensuring a more sustainable future in respect to this aspect of social living.

The more fundamental concepts discussed in this thesis ultimately extend beyond domestic buildings themselves, to asses links between energy consumption and space use within society, revolving around the three key inter-related factors of people, energy and space. What is ultimately meant by ‘space’ will be detailed later, but for now it can be taken simply as a physical space within society inhabited by individuals. At any given moment in time, in order to physically exist within society, an individual must both be inhabiting a space and consuming energy simultaneously. Both energy and space are physically quantifiable, yet defining the scales and extents to which people use each is complex. Energy is constantly consumed by an individual internally in order to physically survive, yet in contemporary society, we extend our energy use far beyond our physical bodies to include the heating and lighting in our homes, and further still through the resources and products we consume from beyond these spaces. This naturally leads to fundamental questions about the extents of space people inhabit within society *through* their energy use, and how this can be defined, quantified, measured and understood. How do the various scales and extents of energy use manifest themselves in the design of our surrounding space, and what implicit motivations lie behind the forms and structures that result from this?

Discussion of these ideas have potentially wide reaching, albeit controversial implications for a diverse range of disciplines across academia. This work therefore draws on literature accordingly, across both natural and social sciences through to architecture and building design. It contributes directly to a growing body of research, building an increased understanding of the fundamental biophysical constraints that govern the development of directed distribution networks, which have now been applied to both natural (West et al., 1997) and social systems (Bettencourt, 2013). Work here continues to broaden the scope of applications to which they can be applied.

At its most fundamental level, this thesis helps to develop a unique, alternative understanding for how our explicit decisions represented in contemporary socio-economic activity translate from implicit decisions, to regulate our ability to access energy and resources within society. Do socio-economic processes and activity, therefore, represent an industrialised extension of these implicit, energy orientated decisions? Is there justification to argue that natural, biophysically grounded laws of growth and scaling help explain, or at least contribute to understanding, quantifiable relationships between anthropogenic use of resources, energy and societal space?

Defining Societal Space and its Dimensions

In order to provide answers to such questions there is a clear need for a deepened understanding of what is ultimately meant by societal 'space', as well as how we define, manipulate and ultimately design this space to meet society's socio-economic requirements. They require answers if we are to fully comprehend the true 'nature' of society, the implicit motivations that drive and explain its inherent characteristics and the explicit form it takes as a result of numerous socio-economic processes. In contemporary society, space itself has become a commodified and valued resource, with intense competition for optimally located spaces and land, particularly in urban environments.

As a result, further questions therefore present themselves as to how we can characterise, and even measure the space inhabited by society, both collectively and from the perspective of an individual. Since the development of standardised mathematical systems society has sought to geographically characterise its surroundings, attempting to measure and break down its physical boundaries across numerous scales and extents. Practical examples would include mapping changes in land use or urbanisation, measuring patterns of energy efficiency between buildings or assessing variation in economic land values, all of which are measured across the spatial dimension. Each of these represents a particular characterisation of associating a given application of socio-economic activity and social practice with a quantifiable unit of societal space.

We ultimately live in both personal and shared space within society. We consume energy and resources as individuals, yet this consumption is facilitated by our social practises and our interactions with others, undertaken across societal space. These social practices are an inherently space filling activity; we transport ourselves through wider society on a daily basis, enhancing our ability to maintain an extended a diverse range of energy consuming behaviours. Our direct energy use at a domestic level is relatively simple to quantify and conceptualise, consumed in the relatively defined unit space of physical buildings, a principle underpins this thesis. Yet, the material products accumulated within a single room of domestic space can contain resources and associated energy from a significantly wider physical space than that occupied by the dwelling itself, and can represent a globally diverse origin of an individual's resource consumption.

Given this, to what extent is the design of our domestic spaces built to facilitate a wider consumption of energy, and how is this design reflected in the size and form of the physical structures themselves? How do individuals perceive the relationship between their energy use and the surrounding space from which this is drawn? As yet there is no fundamental definition of unit space upon which to base this perception, what forms it takes, and how it manifests itself within society. Deepening knowledge of such perceptions could aid in allowing people relate their energy consuming behaviours to surrounding society, building greater understanding of their implications, and how individuals can alter the distribution of their energy use through space and time.

This work aims to challenge traditional, two-dimensional perceptions of spatial utilisation, drawing from a growing body of literature surrounding the behaviour and laws governing space filling directed networks. As alluded to previously, a theoretical understanding of directed networks has been applied across various academic disciplines. These include both natural systems, notably biological organisms (West et al., 1997), and river basins (Rodríguez-Iturbe and Rinaldo, 2001), as well as social systems and infrastructure, notably electricity power distribution (Dalgaard and Strulik, 2011), water and wastewater distributions (Pauliuka et al., 2013) and urban road networks (Bettencourt, 2013). Comparisons can be drawn between the metabolic processing of resources and energy in biological organisms to similar processes occurring in contemporary society. Characterising and defining the space over which these processes occur, using both directed network theory and theories of societal metabolism, could break new ground in understanding how people, both individually and collectively, consume energy and resources across their living space, and develop a new aspect of measurability for which spatial utilisation can be defined. The ideas presented throughout this work therefore aim to build towards an idea of defining societal space by the consumption of energy within it, and to deepen an understanding of the intrinsic links that exist between space and energy use defined by people's social practices and interactions.

Focus and Aims

A central motivation for the research undertaken in this thesis is to test the following research hypotheses. Firstly, that a relationship between energy use and building size should scale, and that this should be sub-linear with an increase in energy efficiency per unit space with increasing building size. Secondly, that this scaling is metabolic in origin, resulting from an optimisation of energy flow from abstraction and distribution through to points of end-use. Such ideas have been suggested and discussed qualitatively from various academic perspectives, as will be seen below. However, they have never tested or speculated directly. These ideas arise from recently published work by Jarvis et al., (2015), who show that, at the global scale, final energy use scales approximately ¾ with respect to primary energy use, a result that begins to question the space over which networked industrial processing operates. Through buildings, this thesis will test the concept that space is directly linked to these points of energy end use, attempting to characterise the variation in energy use across localised spatial scales.

More generally, an underpinning theme of discussion throughout this thesis is to deepen an understanding of the way energy consumed by individuals is fundamentally linked to societal space, both directly through domestic spaces, as well as that consumed from wider society through a globalised distribution of resources. It attempts to build towards a method of characterising the relationship between energy use tied to a unit space, energetically characterising societal space by quantitative, measurable relationships and parameters.

Thesis Aims

Specific aims of this thesis are therefore broken down as follows:

1) To more deeply establish and further understand size related scaling relationships across the UK domestic building stock, notably those relating to household energy use and efficiency in line with current Department for Energy and Climate Change (DECC) research focuses and intentions.

2) To establish underlying causes of any energy related scaling relationships present across the UK building stock, and discuss the origin of such scaling within the context of current literature. To also establish if any energetic scaling relationships can be related to theories of metabolic scaling identified in West et al., (1997).

3) To discuss the wider implications of any scaling beyond domestic spaces up to a societal scale in the context of spatial form, utilisation and design.

4) To reinforce the importance of developing an aspect of measurability for energy use across the spatial dimension and deepen an understanding of how space within society can be defined.

Section 2: **Background and Review**

Analogies of Metabolism in Society

Before delving more deeply into the technical aspects surrounding these hypotheses, it is important to set the context for metabolism as a biological process and previous studies which have drawn comparisons between these processes and contemporary society. Biology defines ‘metabolism’ as an interaction of chemical processes occurring within a living organism to maintain life. Using this, discourse across socio-economic thinking has long entertained the idea that society can be viewed as ‘metabolising’, drawing comparisons to biological organisms in the way in which we acquire, transform, distribute and dispose of our planets natural resources. Fischer-Kowalski, (1998) and Fischer-Kowalski and Hüttler, (1998) discuss the historical development of this conceptualisation across a range of academic perspectives, from its roots in Marxist ideology to its contemporary application in sustainability and socio-economic policy.

Industrial Ecology (IE), a term popularised by Frosch and Gallapoulos (1989), takes an integrated approach towards natural and industrial systems with the aim of improving sustainability of the latter. It focuses on the flow of resources through society, and views the emergent, complex nature of industry holistically, as though it is itself an ecosystem (Erkman, 2001). Industrial ecologists therefore take the characteristics of biological ecosystems, inherently optimised through natural selection, to aid understanding of industrial systems, approaching consequential issues of sustainability, planning, pollution and energy efficiency from a range of academic perspectives (Allenby, 2006). The academic breath of IE therefore extends beyond those relevant to this thesis. However, it does provide context for the idea that biological systems share many analogous characteristics with the various aspects of human society and the development of contemporary industry.

Narrowing down from IE, the idea of Industrial Metabolism (IM), first conceived by Ayres (1988), focuses increasingly on the quantification of resource and energy flows through society, and the direct implications of these on the environment. By characterising the entire flow of all material resources through the industrial process, loss and waste is identified, improving processing efficiency and reducing environmental emission (Anderburg, 1998). More theoretical approaches presented in Ayres and Simonis (1994) introduce the idea that human behaviours act to stabilise a thermodynamic metabolising industrial system, when it is considered as a simple flow of free energy. Despite operating in high thermodynamic disequilibrium, the development of a monetary economic system acts as a stabilising metabolic mechanism in the industrial process, with competitive, market driven supply and demand maintaining a relative steady state. At a functional level, physical quantification of material mass balance through society can be undertaken using Materials Flow Analysis (MFA) and Materials and Energy Flow Accounting (MEFA) methods (Brunner and Rechberger, [2005]; Haberl et al., [2004]). This gives practical application to the resource flow concept, and has allowed societal metabolism to be modelled over wide spatial scales, from entire national economies (Matthews et al., 2000) down to individual households (Carlsson-Kanyama and Karlsson, 2002), a concept that should later prove key to the scope of this thesis.

Fischer-Kowalski and Haberl, (1998) introduce several key conceptualisations linking societies metabolism to land use change and function. Described as a ‘colonisation of nature’, deliberate manipulation of natural systems maintains ecosystem services at a level that would otherwise be unsustainable without human intervention, optimising ecological functions to maximise output. Agriculture and agrarian ecosystems are the prime example of this, where land use productivity is maximised through human alteration to ensure biomass production meets the requirements of anthropogenic demand. Also described is the way in which industrialised society has extended its metabolism beyond manipulation of ecosystems to access geological materials and resources outside the traditional biological system, allowing societal growth beyond what biological limitations would allow.

The flows of materials, people and energy through society have been subject to a variety of qualitative perspectives and interpretations in sociology, summarised in Rapoport (2011). In contemporary academic thinking, urban political ecology characterises this artificial distinction between nature and society, with built environments representing a ‘urbanisation of nature’ by society (Swyngedouw and Kaika, 2008). Given this, cities, buildings and urban environments generally are perhaps the most fascinating and easily conceivable representations of metabolism operating in society. Sociologically, a city as a functional unit can be viewed as a complex accumulation of social, cultural, economic and ecological processes, constantly interacting with one other to create a physical ‘footprint’ of societal metabolism at a given point in space (Swyngedouw, 2006), each unit fulfilling a similar socio-economic function. Ultimately, they embody a physical manifestation of multiple integrated socio-economic networks visible on the earth’s surface, regarded as the most complex of systems created by humanity (Brunner, 2007).

When drawing comparisons between cities, each could be perceived as being both explicitly diverse in culture and character, yet implicitly similar in structural design and socio-economic function. From an individual perspective, cities appear disordered and chaotic, a seemingly random accumulation of social interactions and socio-economic activity, allowing individuals to develop unique perceptions of their surrounding space. When viewed more holistically, super-imposed on this apparent disorder is a growing body of research detailing cities as networks of self-similar fractal patterns facilitating growth and development. They represent an epitome of complex systems in that they are emergent, operate in high disequilibrium and host to significant flows of energy in order to maintain their socio-economic functionality (Batty, 2008). They draw natural comparisons to biological systems through the inherent shift toward optimisation of these energies across space and time, with the development of structured, hierarchical networks ordered in accordance with rules of spatial competition (Batty et al., 2008).

Based on this, recent developments in understanding the scientific basis for the complex nature of cities have been put forward in a series of papers by Bettencourt et al., (notably

Bettencourt et al., [2008] and Bettencourt et al., [2010], Bettencourt 2013). These describe the way in which various defining features of socio-economic functionality scale with measures of city size, such as crime, innovation and wealth creation, with scaling laws shown to be present in the distribution of material infrastructure and in returns on socio-economic productivity across cities. Bettencourt (2013) takes this idea further, discussing the origins of urban scaling laws using biological analogies and allometry to define the functionality of urban environments in addition to their geometry and form.

All of the above literature draws heavily on biological analogies for inspiration in applying scaling theories to the functionality of urban environments (notably Bettencourt et al., [2008]), and the way in which their characteristic features scale with increasing size. Original theories of allometric scaling are grounded in biological sciences, describing the relationship between metabolism and body size of organisms. Termed 'the surface law', it was originally believed that scaling between metabolism and body size was purely related to geometric constraints and the way in which a 3-dimensonal organism loses heat through a 2-dimensional skin with increasing size (Kleiber, 1932). Modern theories of biological allometric scaling began with Kleiber (1947) who first noted that this relationship did not follow the 2/3 power law predicted by geometric constraints, but was closer to ¾ scaling. Known as Kleibers Law, this 3/4 power law remained unexplained until West, Brown and Enquist (WBE) developed their universal theory for this and many other physiological characteristics of organisms, all shown to be theoretical functions of quarter power scaling (West et al., 1997; West et al., 1999). While the mathematics surrounding their theory is complex, general conceptualisations of the WBE model are simpler to understand. Viewing organisms as complex material distribution systems, surface areas and volumes remain key concepts, yet these are focused on the internal geometry of linear transport networks, branching to supply the entire organism. While debate still exists surrounding the consistency of quarter power scaling laws in explaining different aspects of biological systems (Agutter and Wheatley, 2004), it is becoming increasingly accepted as an accurate characterisation for describing the functionality of organisms (Savage et al., 2004). Additionally, many of the fundamental assumptions that underlie the theory of the WBE model hold true when characterising the form and function of resource distribution networks in socio-economic systems, giving the model a wider reaching application to contemporary society.

The WBE model has later been generalised by Banavar et al. (2010), who demonstrated that the property of quarter power scaling is not restricted to an underlying fractal dimension alone, opening up its potential application to any directed network, including those observed in human society. Like WBE, Banavar et al., illustrate their theory using a model of resource distribution in animals from which the associated scaling laws are derived. In contrast to the WBE model however, quarter power scaling is shown to arise simply when the velocity of flow through the network is matched to the linear dimension of the service volume at points of resource end-use, such as cells, and not as a result of a fractal network itself. They also relate this finding to engineered networks such as globalised electricity distribution and transportation systems.

As alluded to earlier, the key concepts and underpinning network theory behind the development of the WBE model has been extrapolated and broadly applied to numerous natural and social systems which similarly facilitate the acquisition, distribution and consumption of resources in a directed distribution network. Brown et al., (2004), outline a ‘Metabolic Theory of Ecology’, which expands the application of WBE scaling beyond individual organisms across entire biological populations, and sets the precedent for describing metabolic rate as a fundamental biological rate defining the growth characteristics of population dynamics. It is upon this basis which application of the WBE model to social systems, the design and growth of resource distributing infrastructure, is founded. Brown et al., (2011) discuss the metabolic theory shown across biological populations in relation to human society and its associated socio-economic process, observing the scaling relationship between per capita GDP and per capita energy consumption. The exponent given of 0.76 is noted as being akin to exponents given WBE distributions models. They also draw what should now be familiar comparisons between biological and societal ‘metabolisms’ in relation to the processing and distribution of energy and material resources. Most recently Jarvis et al., (2015) take this further, more sophisticatedly characterising Resource Acquisition, Distribution and End-use (RADE) networks across society, as well as their inherent optimisation which underpins the ¾ scaling theory in the WBE model. They observe a scaling exponent of approximately 0.75 (¾) between final energy end use in relation to primary energy use at the global scale. They also introduce the notion of dimensionality of space over which RADE networks occur and inherently occupy, which is important given the 3-dimensional nature over which biological networks are shown to operate, and contrasting the prevailing 2-dimensional Cartesian perception of society.

Buildings: A measure of societal space

Buildings provide an abundant source of clearly defined spaces, uniquely suited for assessing energy use and its relation to spatial size. Buildings are static, occupy a physical space and have numerous definitive, easily measurable characteristics. They are inherently designed to facilitate the interaction between people and their energy use, and in urban settings can be seen as a physical manifestation of social practices undertaken in a given space. While it is ultimately individuals who use energy, people are inherently mobile during social practice. Given that a fundamental component required for social practice is energy use, space can be linked to energy flows through the diversity of social practices that take place in urban environments, specifically buildings and the fixed spaces they occupy.

The flows of energy into buildings, in all its forms, are therefore a critical element of socio-economic metabolism, representing the terminal, end-use elements of the resource distribution system where people, space and energy use coincide. Domestic buildings are designed to facilitate both direct energy consumption from power distribution systems, as well as indirectly through use of material products acquired from wider society, which makes them ideal for exploring the way humans 'metabolise' within a fixed unit space. In societal RADE networks outlined in Jarvis et al., (2015), innovations maintaining an optimised network can occur during acquisition, distribution or end-use, with improvements in the processing efficiency at each stage. Buildings, specifically energy consumption in domestic buildings, represent key points of energy end-use in a RADE network, points at which Jarvis et al., show final energy use is shown to scale approximately ¾ in relation to primary energy use. It would therefore be insightful to assess how the final energy use in domestic buildings scales in relation to its physical size, particularly given that noted by Banavar et al., (2010) on the importance of cells for an optimised biological distribution network, cells being biological equivalent of buildings in this context as functional units of energy end-use.

Considerations for both direct and indirect use of energy should therefore be expressed to the structural design of domestic buildings, and the manner in which they use energy over various spatial scales, forming a physical representation of the energy related space inhabited by individuals in society. The theory discussed here implies that any link or scaling relationship between the spatial dimensions of society and associated energy use should be present in the measurable characteristics of domestic buildings. This relationship could also be generalised to form a metric for inferring energy-space scaling relationships across wider societal space, in both built environments and beyond.

Linking allometric scaling relations to the physical properties of buildings, both domestic and non-domestic, is by no means a new concept. Batty et al., (2008) assess patterns of allometry and scaling in building geometry across London, describing how spatial patterns of geometric scaling are distributed across a city. They make important observations relating to scaling in building geometry, showing how buildings change their physical shape as they scale, highlighting a less than expected increases in building plan area and volume for a given geometric relation to its perimeter. This is plausible given that buildings have requirements for ventilation, access and natural light which may not to conform to standard geometric relations. This study makes no indication however of how energy consumption or efficiency may scale with building size, or how such scaling may be affected by non-geometric building attributes, such as building type or age.

Steadman et al., (2009) also detail relationships between the physical properties and dimensions of domestic buildings and how these scale to accommodate physical habitation and the energy associated with this. They note how the shape of buildings is limited by its requirement to maximise surface area exposure from a need for natural light. Metabolism is also mentioned in the context of domestic buildings. However, this is from the perspective of an individual building, relating its need for heat and light to an organism and not to wider societal metabolism that would set it in the context of this thesis. While they also make noteworthy observations of urban built form and its effects on energy use, there is again no mention of any potential scaling between energy consumption in relation to building size. In contrast, Salat (2009) places a greater focus on energy consumption and efficiency in relation to building size and form, as well as other factors influencing total consumption from buildings. This, however, has similar limitations to the above studies, and is not set in the context of scaling at an individual building level, focusing on aggregated consumption across a city, with no metabolic context for values of energy consumption given.

There have been some attempts to link the concept of metabolism to domestic buildings and household energy consumption. Carlsson-Kanyama and Karlsson (2002) identify household units and domestic spaces as important factors in a wider socio-economic system, accounting for both direct and indirect use of energy by a given household unit. They use the metabolism metaphor to characterise the cyclical flow of materials between a household and its environment, relating this to natural biological systems. While this particular study is highly descriptive, with a focus on energy policy, the underlying concept of household metabolism is one which is central to this work, considering both the direct and indirect energy consumption of a domestic building in a metabolic context. It gives clear theoretical justification to apply widely observed metabolic scaling to domestic buildings at an individual level, having been previously utilised extensively across broader built environments and cities to explain urban phenomena (Bettencourt, 2013).

Recent research conducted by DECC also gives political justification to a need for greater understanding of the manner in which energy is consumed at a domestic level. Fell and King (2012) show that this can vary significantly, even across households deemed relatively comparable, emphasising the role of individual perceptions of energy usage and the effect this can have on total consumption. Significantly, they also note that slight differences in the physical properties of buildings can have a substantial effect on its total energy consumption, with buildings being continually altered, manipulated and improved. This makes understanding the inherent design of domestic spaces of critical importance, as well as emphasising the need to improve the measurability of our total energy consumption, both directly at a domestic level and that taken from wider socio-economic space.

Section 3: **Dataset Specifications and Analysis Methodology**

Dataset Identification and Specification

Analysis conducted throughout this thesis will therefore focus primarily on the relationships between domestic buildings and their associated energy use. In order to complete this effectively, an ideal dataset would contain energy use data, preferably directly measured or metered, for a given unit household as well as a detailed measure of unit space for each of these given households. Obtaining such data over a significant scale and in sufficient detail is challenging, given the physical impracticality of measuring domestic buildings and their energy consumption at this scale, as well as the restricted access to such data given its sensitive nature. Numerous datasets currently exist containing measured building characteristics and their associated energy use, although few contain sufficiently detailed data. The Homes Energy Efficiency Database (HEED) collates address level energy efficiency characteristics of domestic buildings across much of the UK. However, it focuses on physical efficiency measures installed on buildings, rather than their total energy consumption (Energy Saving Trust, 2010). The National Energy Efficiency Data-Framework (NEED) provides more applicable data, collating metered energy consumption data with a defined unit size provided by the Valuations Office Agency. Yet, reports from this framework focus heavily on statistical analysis of collated variables relating energy and building size, offering only a descriptive narrative of results with little discussion, nor access to the raw data required for this thesis (DECC 2012b). Similar research by Mortimer et al., (1999, 2000) analyses energy and building size over a small sample of UK non-domestic buildings. Again, however, any wider discussion of results is limited. The same can be said of the American Commercial Buildings Energy Consumption Survey (CBECS) offering similar analysis with little discussion and readily available raw data.

None of the above datasets provide adequate enough detail or readily accessible data available to test the aims of this thesis effectively. This highlights essentially what is novel about this study in particular, aiming to directly compare household energy consumption against building size for evidence of scaling relationships and the wider implications of these, rather than a narrow focus on measuring and improving energy efficiency per unit space. Physical surveys of domestic buildings collected as part of the English Housing Survey (EHS) provide more definitive measurements, tying energy use to a well-defined unit space, and was the only sizeable dataset identified that contains adequate enough detail to comprehensively assess the thesis aims. The EHS is conducted by the Office for National Statistics (ONS) on behalf of the UK Government, Department for Communities and Local Government (DCLG), and published by DCLG (2013). Data was accessed through the membership of the UK Data Service (UKDS) in November 2013. Data is collated to form the 'English Housing Survey, 2011: Housing Stock Data' dataset. Physical survey data for 14,951 dwellings across England was collected by professional surveyors between April 2010 and March 2012, recorded in a multi-stage random stratified sample. Each dwelling is coded, and therefore no information about its physical location is given. A randomly sampled dataset on this scale should remove any localised variation in energy use, as well as removing external factors which may affect either the size or energy use of each dwelling such as climatic variation. The sampling error associated with this data should therefore be minimal given its size, and represent a strong reflection of the total population of households across England. A more recent EHS, published in DCLG (2014), does not contain the required variables for energy usage in each household to supplement the energy performance data recorded for the survey, and could not therefore be used.

Of the 14,951 dwellings surveyed, 14,386 of these were classified as 'households', where energy usage data is given. The surplus 565 records with no recorded energy use are filtered and removed from analysis. It is assumed that these 14,386 households, as close as possible, cover the entire spectrum of size and energy scales across the UK domestic building stock, as well as a broad range of construction dates, total household incomes and inhabitant demographics. Values for each of these can be found elsewhere within the EHS housing stock data, and will be expanded upon in later analysis. In each of the 14,386 households, 11 energy usage types are listed detailing modelled energy consumption figures for various aspects of energy consumption in domestic buildings, including space and water heating by various fuels, as well as direct electricity consumption by the household (for a full list of these variables see relevant appendices). The values for each of these are derived from the Buildings Research Establishment Domestic Energy Model (BREDEM), which requires measurement of various physical household characteristics such as primary heating fuel, boiler efficiency and household insulation provision etc. The measured variables needed to run the model are collected using Standard Assessment Procedure (SAP) guidelines used for assessing buildings' energy performance. Specifics of SAP and the BREDEM are detailed by the Buildings Research Establishment (BRE) in BRE (2014). Further specifics of the BREDEM variables collected as part of the EHS to ultimately form the given energy consumption values are outlined in EHS (2011). Crucially however, the physical measured size of a given household is not used as a core variable within the BREDEM, which legitimises its use for investigating a scaling relationship between a modelled energy use variable and a measure of spatial size. While using modelled energy data is not ideal, as it will incur error in estimating the energy use for a given unit space, it does allow data to be collected on the scales seen in the EHS, which would not be practical using physically metered data. Total energy consumption for each given household is taken from the sum of each of the 11 energy use types modelled, given in kilowatt-hours per annum (kWh yr^{-1}), the standard unit of measurement used for recording energy consumption in buildings. Using annual energy totals also removes any potential seasonality in energy usage that may arise from climatic variation.

Deriving Building Geometric Properties

Physical household size can be defined by a number of spatial measures, such as plan area or building volume. For the context of this thesis, an ideal measure for unit space would be volumetric, as this captures the full three-dimensional physical space of a given household over which energy is consumed. While the EHS does contain three dimensions of external building measurements, these do not necessarily match the spatial scale over which energy consumption of a given household is measured, as will be detailed below. A measure of Total Floor Area (A_{tf}) is, however, listed within the EHS dataset, corresponding directly to the spatial scale dwelling itself and therefore to the spatial scale over which energy consumption is recorded. Given that A_{tf} will extend itself through the entire dwelling, this measure will to a large extend be directly related to its three dimensional volume, given this measure of space will extend over a number of floors as dwelling height increases.

Geometric scaling relationships between physical building properties such as height, wall area and volume are widely discussed in work mentioned in previous sections, notably Steadman et al., (2009), Batty et al., (2008) and Salat (2009). They are important considerations when assessing household energy consumption given the significant proportion of domestic consumption expended on space heating, estimated at around 70% (Palmer and Cooper, 2011), which can be significantly influenced by the nature and geometry of a building's Exposed Surface Area (A_{es}).

In relation to scaling between energy use and household size, a geometric argument would attempt to account for any observed scaling exponents through consideration of how volume scales with exposed surface area, given it is this area through which heat is lost. A domestic building relates to a well-defined three-dimensional structure. When its form is idealised into standardised shapes, which many buildings are engineered to take, it should therefore be subject to established laws of geometry in the way each building scales with size. One such scaling relation states that surface area scales 2/3 with its volume. Specifically, a growth in surface area should occur at a rate of approximately 2/3 the rate of growth in volume for a given increase in unit size, representing the relative dimensionality of each variable. Assuming heat loss from a building's internal volume is through the entire exposed surface area, then we should expect scaling between domestic energy consumption and a measure of space should approach a value of 2/3, given the predominance of space heating in the domestic energy profile.

2/3 scaling between surface area and volume can be easily derived mathematically, and has been previously done so in Batty et al., (2008), who discuss several notable scaling relations for building geometric properties. If we assume a building to be shaped as a box with a given length, L, then the 2/3 scaling relation between exposed surface area (A_{es} in equations (1) and (2) below) and volume, V, can be derived as follows:

$$A_{es} = 5L^2 \qquad (1)$$

$$V = L^3 \qquad (2)$$

Therefore, $L = (A_{es}/5)^{1/2}$ and $V = (A_{es}/5)^{3/2}$.

An estimate for both exposed surface area and building volume can be derived directly from the measure of total floor area if assumptions are made about the building's form. Both require a measure of a given building's vertical height. Unfortunately, data collected to form the EHS housing stock for building height and its number of floors relates to the external geometry of surveyed buildings, and do not necessarily correspond to the dwelling over which total floor area and energy consumption are measured. For example, a block of flats may represent the external structure of a measured building, yet a dwelling may only be one flat within the main block. Such data can still be useful however. For buildings across the entire housing stock of 14,591 households, information on the number of floors of a given building, as well as its main eve height are recorded, which can be used to give an estimate for the average height of a given floor. These relate to the external dimensions of a dwellings outer building, and therefore cannot be used directly to estimate H. When eve height is plotted against the number of floors (Figure 1), linear regression between these gives a value of 2.54m per floor, which seems reasonable as an estimate of average floor height in a typical domestic building.

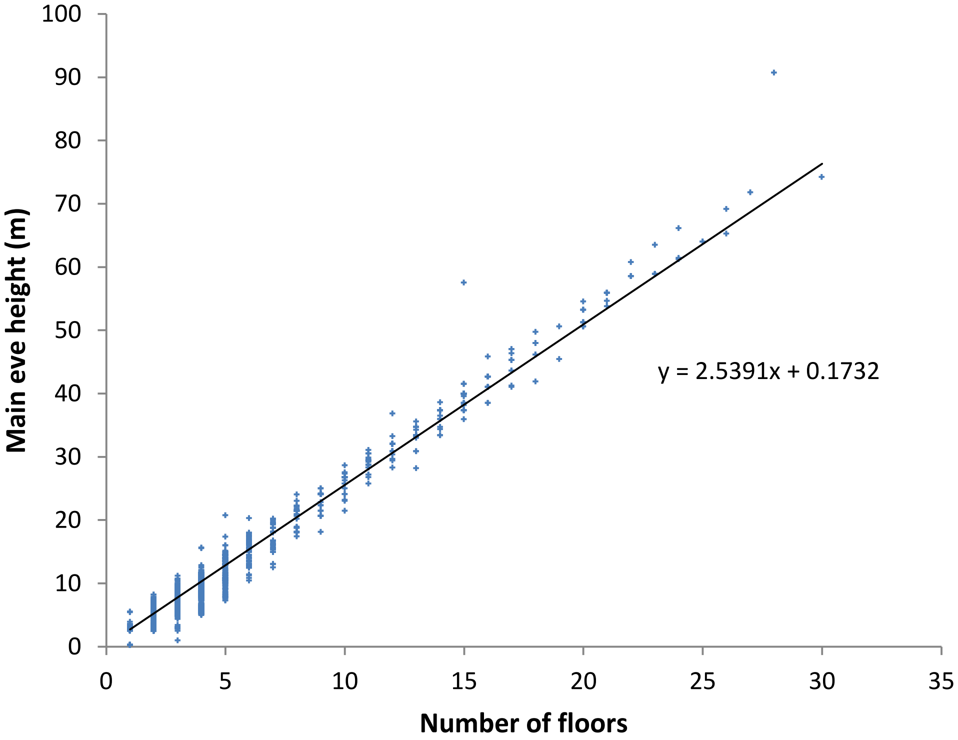

Figure 1: Linear regression between the number of floors of a given building against the measure of the building's main eve height (the vertical distance between the ground and the point at which the roof begins to slope). Data plotted for all 14,951 households surveyed to form the EHS housing stock. Linear regression gives a trend line slope of 2.5391 ± 0.009 (for full analysis see relevant appendices).

With an established value for the height of a given floor, accounting for a variable house height is now possible, allowing estimates of exposed surface area and volume to be derived. While data for the number of floors again relates to external building measurements, dwellings defined as a 'single unit' can be filtered, where the external dimensions of the physical building match the dwelling itself. Of the original 14,951 households, 11,293 of these classify as single units. An estimate for exposed surface area for each single unit building can be extracted from its total floor area, as well as values given for the number of floors in a given household and the main eve height of the household. The exposed surface area (A_{es}) can be characterised using equation (3), where *R* is the Roof Area, *W* is the Width of a given side, and *H* is the height of the building.

$$A_{es} = R + 4WH \tag{3}$$

Taking the number of floors in the single unit households as N, the total floor area (A_{tf}) can now be distributed over a number of storeys to represent true building form as accurately as possible. The roof area, R, is taken to be equal to the value of one floor (equation 4). The building width, W, can therefore be redefined as the square root of R (equation 5). Given the individual floor height derived in Figure 1, the overall building height, H, can now be estimated using the number of floors, N, given only single unit dwellings are being considered (equation 6). These can be applied to Equation 1 to gain an estimate of exposed surface area.

$$R = A_{tf}/N \tag{4}$$

$$W = \sqrt{R} \tag{5}$$

$$H = 2.54N \tag{6}$$

The volume, V, can also be estimated from similar values, taking the ground floor plan area (R, given that roof area covers the spatial area as any given floor) and building height, H, as defined by equation 7.

$$V = RH \tag{7}$$

When equation 7 is applied across all single unit dwellings, both A_{tf} and V will scale linearly with one another (Figure 2) given that, $V = 2.54N(A_{tf}/N)$ and hence, $V = 2.54A_{tf}$. While building height is variable by the number of floors, N, the total floor area is divided equally over each floor, mitigating this variability in height. This estimate of building volume assumes that the height of any given floor, taken as 2.54m from Figure 1, is conserved, and does not itself scale with building size. While this may be true for most domestic spaces and rooms within a building, it may not account for non-conventional spaces such has stairwells, access corridors and utilised attic space. However, these generally form a low proportion of the total space occupied by a given building, meaning the effects of any non-linearity in floor height from such spaces should be minimal.

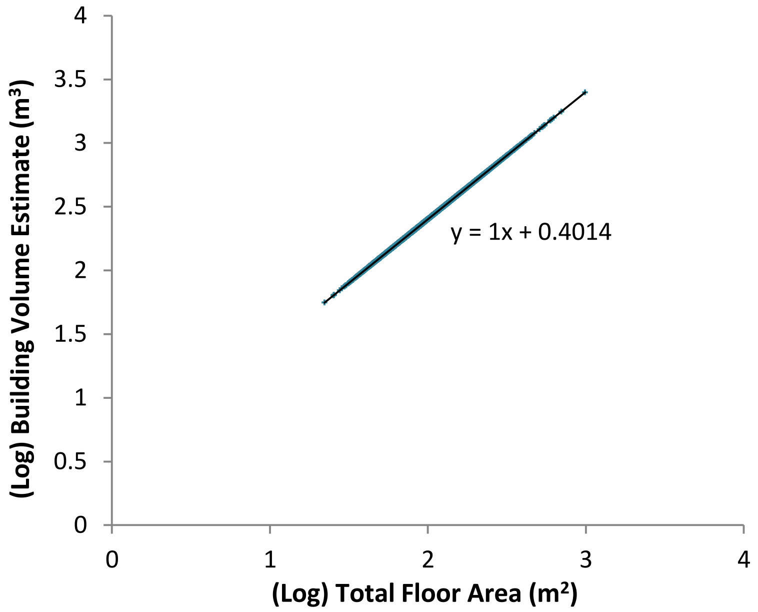

Figure 2: Linear regression between log transformed total floor area (A_{tf}) (m^2) and Volume (V) (m^3) plotted for all single unit households a scaling exponent of 1.0 is observed, indicating linear scaling between each.

Hence, if we assume this estimate of V is representative of the true volume of the dwelling, then for the purposes of analysis A_{tf} and V can therefore be used interchangeably given one is shown to be a direct relation of the other. Given this, applying equations 4, 5 and 6 together into equation 3, the scaling in Figure 3 between total floor area (A_{tf}) and the estimated exposed surface area (A_{es}) gives an exponent of 0.656 ± 0.001. This value lies close to the theorised 0.67 (2/3), expected given this method of deriving both A_{es} and V idealises building form. As noted in Batty et al., (2008) there may be issues with inferring building form and surface area in this way, and may scale differently to that expected by standard allometric theory. Buildings are inherently designed to both minimise exposed surface area to reduce heat loss, but also maximise this area in relation to ventilation and natural light, in what Salat (2009) terms the 'shape factor'. Idealising building form using this methodology reduces any influence or consideration of this. It is also important to note that these estimates of exposed area and volume are only taken from single unit households, and not from the entire EHS housing stock. These are most likely constitute detached, semi-detached and terrace housing, with the exclusion of tower block flats and non-conventional dwellings, which are those most likely to deviate from a conventional 2/3 scaling between volume and surface area.

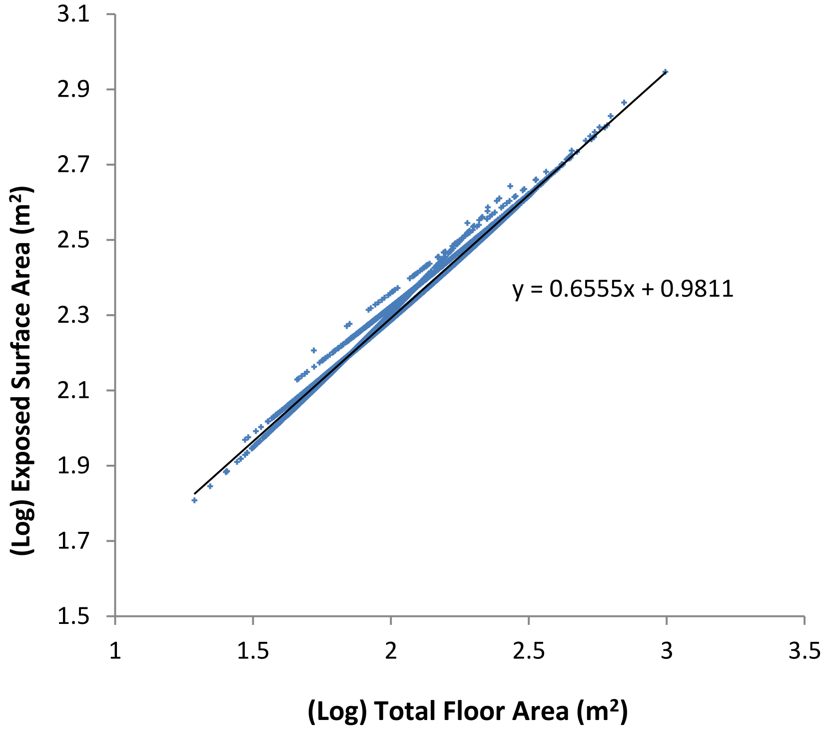

Figure 3: Linear regression between log transformed total floor area (A_{tf}) (m^2) and estimated exposed surface area (A_{es}) (m^2) for all single unit households. Observed scaling exponent of 0.656 ± 0.001 indicated by the main trend line.

Considering this, total household floor area (T_{fa}) given in metres (m^2) will be taken as the spatial measure for establishing scaling relationships between energy and space across the EHS housing stock, given this can be applied most accurately across all households where energy usage is recorded. The first of these is applied across the entire dataset in Figure 4. Any Further analysis methodologies will be explained when appropriate.

Section 4: **Analysis and Results**

Scaling Across the UK Housing Stock

First, energy consumption for each of the 14,386 households is plotted against the total floor space area associated with this consumption, allowing an initial insight into the way in which domestic energy use varies with increasing spatial scale. This, like each scaling exponent to follow, is established using linear regression of log transformed data of each given variable. The margin of error surrounding each exponent is based on 95% Confidence intervals (CI), with full statistical analysis of each exponent listed in the Appendices. Figure 4 indicates a positive, scaling relationship between energy consumption and household size. This trend is unsurprising, as it would be expected, potentially even assumed, that a general positive trend between increasing spatial area and energy use would be observed. Plotted log-log, this relationship is shown to hold over approximately 2 orders of magnitude with respect to household size, as defined by its floor space area, and 1.5 orders of magnitude in relation to energy use. The relationship is shown to be sub-linear, with an observed scaling exponent of **0.803 ± 0.013**. This indicates a scale related energy efficiency increase with increasing spatial size. The 0.8032 scaling exponent from Figure 4 will henceforth be referred to as exponent *X*.

Before the causes and wider reaching implications of this scaling are discussed, further detail within the EHS allows households to be classified more diversely. Other attributes relating to the physical household type or the demographic of its inhabitants may have a significant influence over the nature and extent of energetic scaling relations across UK domestic buildings. The dataset can be reclassified and broken down by these attributes, allowing energy-space scaling exponents to be estimated for each of the factors within a given attribute. This should give a more detailed insight into patterns of scaling across the UK domestic building stock.

Initially, the housing stock can be sub-divided to assess the different components and structure types that aggregate together to produce *X.* As is also shown in Figure 4 and coloured accordingly, variation can be observed between individual scaling exponents of differing household types. When the scaling exponent of each household type is considered individually, all trend lower than *X*. As would be expected, purpose built flats (blue) are generally both lower energy use and smaller in total floor area, scaling with an exponent of 0.626 (±0.035). Similarly, single units (green) which form the majority of households surveyed, scale with a 0.595 (±0.015) exponent, yet extend up to larger floor areas and energy use totals expected of large detached buildings. More in depth data classification is explored below.

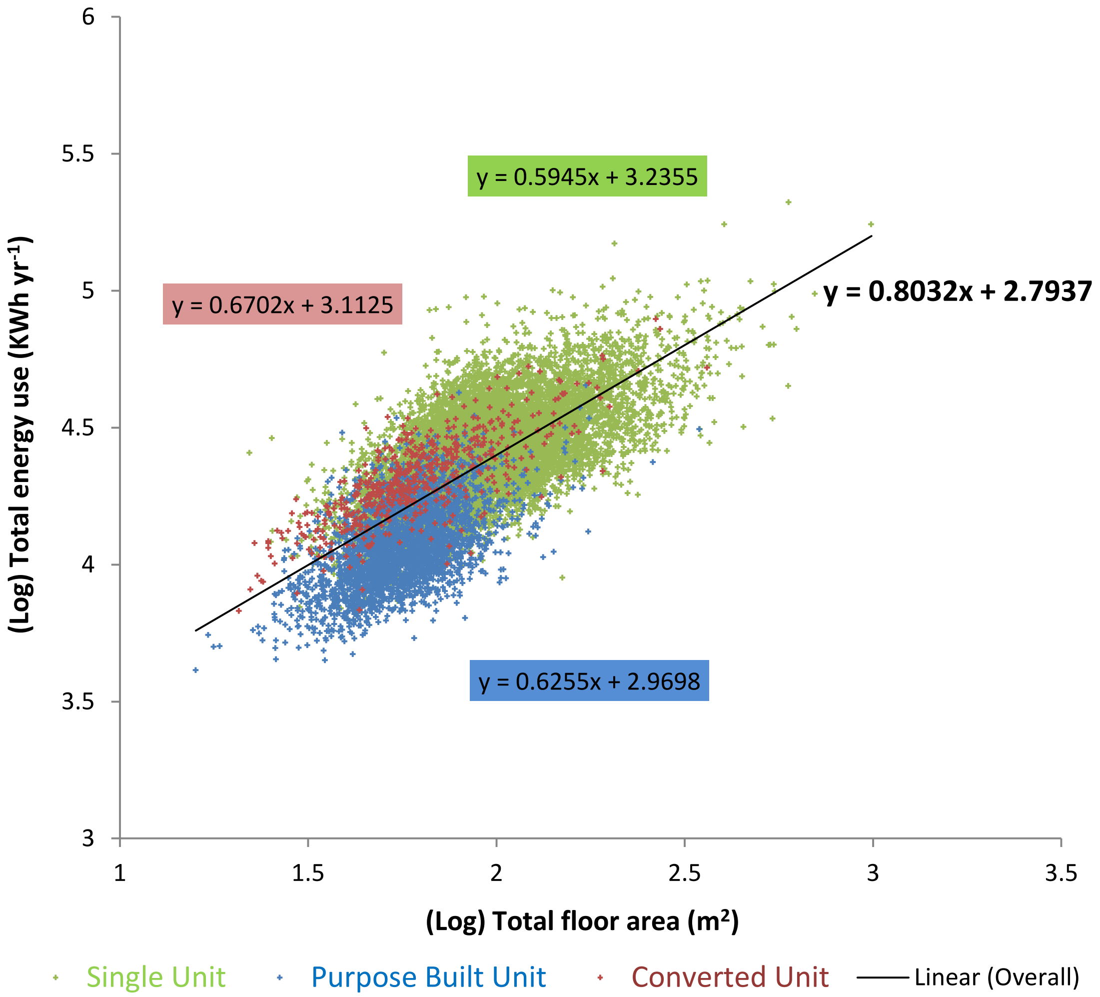

Figure 4: Linear regression between log transformed total floor area (A_{tf}) (m^2) and estimated energy use (kWh yr^{-1}) for all 14,386 households where energy usage was recorded. Data has also been reclassified and scaled as follows: Single units (green) represent buildings identified as a self-contained single unit household, such as terrace, semi-detached or detached buildings (0.595 ±0.015). Flats and apartments are represented as purpose built (blue) units, where original construction of the building was for domestic habitation (0.626 ±0.035). Converted units (red) represent households where a building was originally built for non-domestic use, but later converted (0.670 ±0.045). Scaling across all 14,386 households is given by the black linear trend line with a scaling exponent **0.803 ± 0.013.**

Sub-Unity Scaling Between Household Classifications

Further detail within the EHS allows single unit households to be classified more diversely, distinguishing between terrace, semi-detached and detached buildings, helping to assess more individual differences in scaling's between different household types. Scaling exponents for each of these are given in Table 1, with more detailed statistics found in the Appendices. With the exception of 26 households classified as 'temporary', where no correlation was observed between spatial area and energy use, all but detached households scale between 0.62 and 0.68. In contrast, the scaling exponent for detached households is 0.449 (±0.028), distinctly different to all other household types, indicating a more pronounced decline in energy use per unit space with increasing size. This difference is interesting given that detached buildings represent a more physically independent space of consumption, sharing no physical attachment to other points of energy end use. It is also interesting in itself that no individual household type scales comparatively with X (~0.8), indicating that any laws governing scaling of energy use with building size behave differently at an individual building scale or across a given household type, than they do when all domestic spaces are considered collectively.

Table 1: EHS housing stock data classified by household type, recorded as part of building physical survey. Purposes built flats contain households where original use of housing block was for domestic use. Converted flats contain households where the original use was non-domestic, but later converted. Non-domestic plus flat contain households where wider building has both domestic and non-domestic use. Scaling exponent is based a linear regression between log transformed household total energy consumption and total floor space area. Significance based on 95% CI.

Household Type	Scaling Exponent	95% CI	Total Number
End Terrace	0.645	±0.051	1645
Mid Terrae	0.645	±0.035	2793
Semi-Detached	0.631	±0.028	3989
Detached	0.449	±0.028	2551
Temporary	0.155*	±0.322	26
Purpose Built Flat	0.624	±0.035	2867
Converted Flat	0.678	±0.050	499
Non-domestic Plus Flat	0.650	±0.206	16
Total (X)	*0.803*	*±0.013*	*14386*

**no correlation observed between energy consumption and floor space area.*

Several demographic influences on scaling can also be identified from the EHS dataset. Table 2 shows the housing stock broken down by the number of inhabitants occupying a given household, reclassified in a similar manor to above. For households with one to four inhabitants, a significant pattern of scaling can be identified, with a decreasing value of scaling exponent with increasing inhabitants. This would indicate that the amount of energy consumed per unit space decreases with increasing household size with an increased number of inhabitants, with relatively less energy consumed in a household with four inhabitants than one with a single inhabitant for a given unit size. This result is unsurprising given that individuals in a shared household will naturally share their energy consumption and undertake certain practices simultaneously, for example the use of heating and lighting. Exponents for households with five, six and seven plus inhabitants show a much less distinct pattern in scaling variation, even showing exponents tending back towards 1.0. This may suggest an additional factor or social practise having an increasingly dominant effect on any scaling, more prominent than the influence of shared direct consumption. The significance of these values is, however, more questionable, given the lower number of such households present in the housing stock.

Table 2: EHS housing stock data classified by the number of people occupying a given household, recorded as part of the EHS Scaling exponent is based a linear regression between log transformed household total energy consumption and total floor space area. Significance based on 95% CI.

Number of People	Scaling Exponent	95% CI	Total Number
1	0.849	±0.026	4105
2	0.705	±0.023	4984
3	0.718	±0.039	2279
4	0.658	±0.037	1927
5	0.701	±0.059	692
6	0.805	±0.088	266
7 +	0.771	±0.113	133
Total (X)	*0.803*	*±0.013*	*14386*

Next, Table 3 shows scaling exponents for data reclassified by the total household income of their inhabitants, classified into income bands from individual values of income listed in the EHS dataset. Higher incomes generally see a larger decrease in energy consumed per unit space with increasing household size, and hence a more pronounced increase in energy efficiency with increased household size. So while all households across all levels of income show a decrease in energy consumed per unit space with increased household size, this effect is shown to be more pronounced in households with higher total incomes. There is a slight increase in the exponent back towards 1.0 in the 50-60k bracket which contradicts trend across the rest of the income classification. This, however, could be attributed to the increased uncertainty that surrounds each of the exponents at this end of the scale, with a lower total number of households from which each scaling exponent is derived.

Table 3: EHS housing stock data classified by bands of recorded total household income, recorded as part of household survey. Scaling exponent is based a linear regression between log transformed household total energy consumption and total floor space area. Significance based on 95% CI.

Total Household Income	Scaling Exponent	95% CI	Total Number
£0-10k	0.869	±0.046	1370
£10-15k	0.888	±0.035	2765
£15-20k	0.856	±0.038	2543
£20-25k	0.831	±0.043	1955
£25-30k	0.738	±0.044	1537
£30-35k	0.744	±0.055	1070
£35-40k	0.726	±0.059	785
£40-50k	0.647	±0.047	1059
£50-60k	0.715	±0.069	539
£60k+	0.657	±0.051	763
Total (X)	*0.803*	*±0.013*	*14386*

Data can also be reclassified based on its period of construction. This may influence the nature of any scaling relationship between energy and household size given that developments in energy efficiency technology occur through time, and are ultimately incorporated into newly designed structures. Exact dates of construction for each individual household are not given, with each classified into a construction period given in the first column of Table 4. The scaling exponents listed in Table 4 tend towards linearity as dates of construction become more recent, with a significant difference between exponents of the oldest and newest households. Similar to each of the tables above, energy consumption scales sub-linearly across all construction dates, with a decrease in the energy used per unit space with increased household size. This decrease is, however, less pronounced in those of newer construction. While Error bounds around each scaling exponent draw each value closer together than they initially appear, a statistically significant difference between the oldest and newest households remains. This contrasts what would intuitively be expected, which would have the newest and largest households having the greatest efficiency, using the least energy per unit space. An explanation for this could lie in the effect of geometrics on the scaling relationship between energy and building size, with the overall shape and form of the building's structure influencing the way a given building consumes energy with changing size. This effect may also help in explaining several other sub-unity scaling exponents listed across Tables 1-4, and will be expanded upon in the following section.

Table 4: EHS housing stock data classified by date of construction, recorded as part of household survey. Scaling exponent is based a linear regression between log transformed household total energy consumption and total floor space area. Significance based on 95% CI.

Date of Construction	Scaling Exponent	95% CI	Total Number
pre1850	0.629	±0.046	399
1850-1899	0.699	±0.033	1200
1900-1918	0.696	±0.039	1051
1919-1944	0.631	±0.031	2259
1945-1964	0.705	±0.028	3182
1965-1974	0.822	±0.033	2192
1975-1980	0.822	±0.038	1030
1981-1990	0.848	±0.033	1209
1991-1995	0.875	±0.046	480
1996-2002	0.786	±0.039	643
post2002	0.835	±0.035	741
Total (X)	*0.803*	*±0.013*	*14386*

Finally, data across all 14,386 households can be reclassified by specific energy usage characteristics, reflecting potential differences in scaling in relation to specific modes of energy consumption. As described in Section 3, 11 energy usage types are estimated for households across the EHS, which are summed to give an estimated total energy usage for a given household. A full list of energy usages types can be found in Appendices Table 1A.

These 11 usage types can be broken into three distinct categories, defined as *energy used for space heating, energy used for water heating* and *energy used for cooking, lighting and appliances.* Scaling relationships for each category are applied over all 14,386 households, exponents of which can be found in Table 5.

Table 5: EHS housing stock data reclassified by specific modes of energy consumption. Scaling exponents are based a linear regression between log transformed household energy consumption and total floor space area. Significance based on 95% CI.

Energy Usage Type	Scaling Exponent	95% CI	Total Number
Space Heating	0.965	±0.019	14386
Water Heating	0.419	±0.017	14386
Cooking and Appliances	0.595	±0.009	14386

Energy used for space heating is shown to scale near linearly, with almost no decrease in the energy used for space heating per unit space with increasing building size. In contrast, exponents for water heating and domestic social activities show a significant decrease in the energy used per unit space for each of these practices.

Section 5: **Discussion and Wider Implications**

Origins and Interpretation of Scaling Exponents

Geometric Influences on Scaling

The influence of building geometry and other geometric properties could help to explain patterns in sub-unity scaling detailed across Tables 1 to 5, as well as influence the unified scaling exponent (*X*) from Figure 4 in relation to energy use and household size.

Both Figure 4 and Tables 1-5 highlight notable differences between exponent *X* and sub-unity scaling exponents based on specific household characteristics. Exponent *X* gives a value of ~0.8, differing from single unit households (generally detached, semi-detached and terrace) scaling with a ~0.6 exponent, and from detached houses alone (Table 1) which scale with a ~0.45 exponent.

Each classification in Table 1 is based on a specific household type, with distinct geometric properties and ranges of spatial scale. Larger and detached buildings will have a relatively high initial marginal sensitivity to changes in energy consumption for increases in building size, with a greater proportion of exposed wall area generating heat loss. Exponent *X* in Figure 4 represents a function of all offsets generated by different spatial and geometric properties across all household types, visible when data is reclassified by specific building characteristics. Exponent *X* forms an empirical mix of all sub-unity scaling relationships, across a broad range of spatial domains, from the smallest flats to the largest detached buildings. This may help to explain the differences in offset between exponent *X* and the sub-unity exponents in Figure 4 and Table 1.

This would also suggest building geometric properties play an important role in governing patterns of scaling between energy consumption and spatial size. Many sub-unity scaling exponents through Tables 1 to 4 show patterns of exponents which trend either towards or away from ~2/3 exponent, suggesting a geometric influence on scaling when the dataset is redefined by certain household characteristics.

As listed in Table 1, with the exception of detached buildings, scaling exponents for all other household types lie in the region of ~2/3, which, contrary to Figure 4, suggests a strong influence of geometry when each household type is considered alone. Both types of flats also scale as such, which is surprising given these are those least likely to lose energy through heat loss through an exposed wall area. The difference in scaling observed in detached buildings (0.449 ± 0.028) could relate to abnormal external geometry, indicating energy is conserved per unit space at a much faster rate than an idealised geometry alone would suggest. This could result from an increasing use of complex geometric shapes used in the structural design of these buildings, formed to maintain optimal plan depths that allow open air ventilation and natural light, as well as adequate access corridors between individual rooms (Steadman et al., 2009). Semi-detached and terrace buildings, as well as flats are more commonly associated with more densely populated urban settings, where competition for space is intense, with buildings increasingly subject to external influences a linked networked architecture to other buildings, as well as aggregating effects of the wider urban environment influencing their form and geometry (Batty et al., 2008, Salat, 2009).

Table 3 is somewhat different, in that it begins to consider the role social and demographic factors may have in relation to scaling between energy and space. As household income increases, scaling exponents trend from being near linear for the lowest income brackets (~0.85), becoming increasingly sublinear down to a limit ~2/3 when income exceeds £40k. This makes sense given households with larger incomes will typically be able to afford measures to improve the physical structure of the building, with more free capital to invest in energy saving measures, ensuring losses from the property are minimised. It is notable that exponents appear to become increasingly sublinear with increased income, yet limited to a value ~2/3, which could denote the point at which individuals ability to influence physical energy losses from their household are limited by building geometry. It is also notable that exponents begin to decrease suddenly between incomes of £25k - £40k, before which exponents generally remain around ~0.85. This could relate to the point at which home ownership begins to affect people's ability to influence their domestic surroundings, with a heightened sense of permanence about their surroundings. It may also relate to the point additional capital becomes available as disposable income, giving individuals a greater marginal propensity to invest in energy saving measures. This is interesting given the clear social implications, but also given such investments in energy efficiency will generate future socio-economic returns and wealth dividends. It is noteworthy however that Table 3 gives no indication of the range of scales over which each exponent is based. This may be important, given households used to derive an exponent for lower income brackets are likely to be taken from those of smaller spatial size and from a much narrower range of spatial scale.

Like Table 3, the trend in exponents listed in Table 4 appear to be roughly bounded by values ~2/3. Those which are considered oldest, based on their date of construction, appear to be more significantly influenced by geometric heat losses than those of newer construction, with exponents tending towards linearity with decreasing age. This may indicate how innovation in relation to building energy efficiency over time has gradually decoupled the energy use characteristics of domestic space from its physical geometric constraints, with newer households more readily adaptable to such technologies. While many innovations such as double glazed windows and roof insulation can be retrofitted to older buildings, incorporating such innovations into a building's initial design will naturally produce more significant efficiency gains. As such, newer buildings are more likely to have modern levels of material consumption, use of electricals and central heating systems considered in their design, allowing each of these to be utilised most efficiently.

Table 5 gives an indication that a reduction in energy usage per unit space with increased household size comes predominantly from energy used for water heating and domestic social activities, such as cooking and the use of electrical appliances, rather than from energy used for space heating. This relates directly to exponent X, which considers total household energy use, being a function of its offsets. It suggests the reduction in energy consumed per unit space across the UK housing stock relates to a reduction in energy used per unit space for water heating and domestic appliances.

Given this, it follows logically to assess the way in which household energy consumption scales with estimated exposed surface area (A_{es}). This relationship should scale somewhere approaching linearity if scaling between A_{tf} and energy consumption in domestic buildings is dominated by a net heat loss through the exposed area. The linear regression from Figure 5 for single unit households gives an exponent of 0.895 ± 0.022, indicating a decrease in energy consumed per unit of A_{es} with increased building size. This provides compelling evidence to suggest that scaling between energy consumption and building size may not be solely related to its geometric principles, given energy is still being conserved when building spatial size is defined by its exposed surface area. This is based on assumptions that heat loss alone scales linearly with $A_{es,}$ and that no other aspect of domestic energy use is directly influenced by A_{es}.

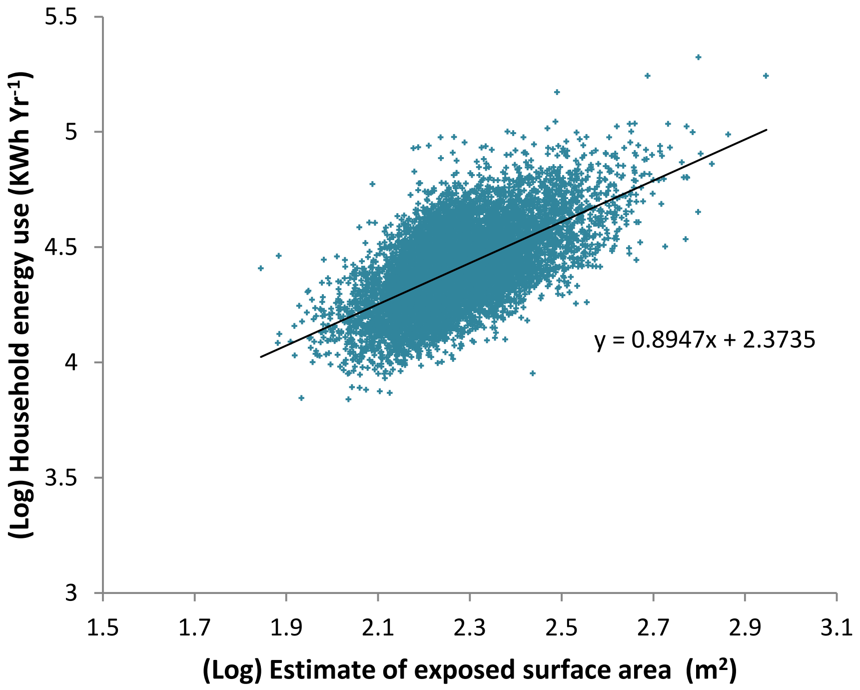

Figure 5: Linear Regression of log transformed Exposed surface area (A_{es}) (m^2) and household energy use (kWh yr^{-1}). Observed scaling exponent of 0.8947 ± 0.022 indicated by the main trend line.

It should again be noted that the values of energy usage used to form this scaling come only from single unit households, i.e. when the external measurements of a given building match the dwelling over which energy consumption and A_{tf} are measured. As is shown in Figure 4, sub-unity scaling between energy use and A_{tf} is shown to be significantly different to that for households across the entire EHS dataset, and hence must be taken into consideration when using single unit households to represent domestic buildings as a whole. Contrary to this however, even within single unit households, heat loss will not be evenly distributed across the whole estimated A_{es} given some buildings will be semi-detached and terrace housing. These households will have distinct and significant boundaries which connect them to similar domestic space, with no loss or gain of energy. Loss to the surrounding environment would be minimised with a lower proportion of A_{es} relative to detached buildings. This effect will be even more prominent in dwellings such as flats and apartments in large tower blocks, the majority of which will not be considered in Figure 5, as these generally do not constitute single unit dwellings.

Additionally, as has already been eluded to previously, the relative accuracy of the metric used to measure space in each building needs to be considered. While a measure of total floor space area (A_{tf}) will incorporate the majority of space over which energy is consumed and utilised by social activity, there may be discrepancies between this area and the actual space inhabited by those utilising it. Physical buildings themselves are very obviously three dimensional structures, meaning while A_{tf} generally extends itself over a number of floors, this measure may either under or over account for variations in height across the third dimension. Estimates for volume derived in Section 3 scale linearly with A_{tf} (Figure 2), given that this estimate is derived directly from the floor area, and can only be completed for single unit households. A linear scaling my not be the case in reality.

Building geometry clearly influences the scaling relation between domestic energy and space use, yet the scaling relationship observed in Figure 4 is unlikely to relate purely to geometric constraints, given space heating is only one of several aspects of domestic energy use. Many of the sub-unity scaling exponents listed in Tables 1-4 seem bounded by values ~2/3, indicating a lower geometric limit defined by space heating on the capacity of a given building to improve its scale related energy efficiency. Exponents which trend or deviate away from values ~2/3, or exponents that scale differently when considered holistically like exponent *X*, must but attributed to other aspects of domestic energy consumption. While space heating constitutes the majority consumption of energy in domestic buildings (Palmer and Cooper, 2011), energy consumed by domestic activity is also likely to scale with increasing building size, given certain practices require a fixed amount of energy regardless of building size (boiling a kettle, for example). This assertion may help to explain the pattern of scaling observed in Table 5. Such activity offers significant potential for individuals to utilise and manipulate domestic space, through physical modifications to buildings themselves and through products acquired from wider society that form part of contemporary domestic consumption.

Metabolic Influences on Scaling

What other factors, therefore, may influence exponent *X* and drive an apparent inherent increase in energy efficiency with increased household size? Answers may lie in the extensive discussion surrounding the metabolic process, and the comparisons it draws between biological organisms and societal processing of resources, both at a domestic level and beyond. There is also a notable similarity in the character of scaling observed in Figure 4 to that observed in biological systems (West et al., 1997, Brown et al., 2004), which warrants investigation into whether exponent *X* can be attributed, be it partly or wholly, to a metabolic process. A number of underlying assumptions listed in West et al., for the WBE model of metabolic scaling draw many analogous comparisons to societal resource distribution, which include a distribution of resources in a branching fractal like pattern, and an inherent minimisation of energy losses through the system.

The arguments presented below offer an alternative, more theoretical explanation for the observed scaling in Figure 4 to those presented above. They are founded on the basis that an individual's energy use both dictates and is dictated by the form and function of their surrounding societal space, and that the explicit structure of this space is designed to facilitate the consumption of energy and resources by individuals, following laws of biological metabolism (West et al., 1997). On this basis, it makes sense to redefine the scaling between energy and unit size given in Figure 4 per capita, given the focus on individuals this argument takes as well as the more fundamental nature with which space and energy use are conceived. With the same data for the number of household inhabitants used in Table 2, Figure 6 scales both energy per capita and A_{tf} per capita to give a new exponent for domestic building energy use. This new exponent is shown to be **0.838 ± 0.001**. This is a slight increase on exponent X from Figure 4, with a slightly less pronounced increase in energy efficiency per unit space with increased household size when each is taken per capita. The data appears less dispersed and more focused along the main trend line, than that from Figure 4. This exponent is also notably further than *X* from the 0.75 exponent found in many aforementioned studies of metabolic scaling, expected if energy-space scaling in domestic buildings were to follow completely these existing theories.

Nonetheless, all exponents given thus far indicate a possible optimisation of energy use across domestic buildings with increased building size, which cannot be attributed solely to the buildings geometric properties. A metabolic influence on energy usage scaling across domestic buildings would be indicative of implicit characteristics of human behaviour, to optimise their energy use, both present and future, at a given point in space following inherent laws of biological origin. This optimisation can be related to a fundamental nature of human behaviour, with domestic space representing a physical manifestation of implicit behaviours to consume energy in a manner that is most efficient in space and time.

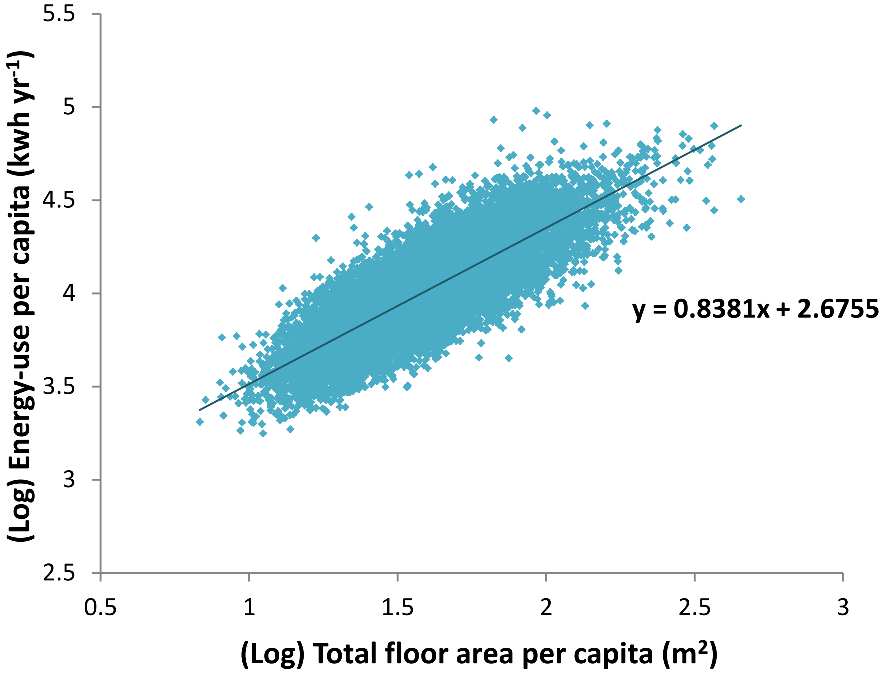

Figure 6: Linear regression between log transformed total floor area (A_{tf}) (m^2) per capita and recorded energy use (kWh yr^{-1}) per capita, for all 14,386 households where energy usage was recorded. Scaling exponent indicated by the main trend line is recorded as 0.838 ± 0.001.

If, for ease of understanding, we assume an individual newly operating in society acquires a domestic building of similarly new construction, the overall scale and design of this building would be representative of their ability to consume energy and resources at that given moment. Increasing accumulation of capital wealth over time, however, increases capacity of an inherently mobile individual to consume energy in an inherently immobile physical space. The level of consumption per unit of domestic space therefore increases, given the static nature of domestic buildings. An individual would therefore seek to further optimise their energy use by manipulating the space, in order to keep their ability to use energy optimal in both space and time. While this manipulation should theoretically present itself across all scales of physical space, the immediate surroundings of an individual are where these optimisations are most likely to physically manifest themselves; in material and immaterial personal processions and physical form of building structures.

Some of these are relatively simple to characterise and relate directly to improving the energy efficiency of the physical building itself, such as installing loft insulation, double glazing or solar panels to name but a few, which have seen increased uptake over recent years (Hamilton et al., 2014). Others are however more abstract, represented in an individual's social practice and their interactions with others across society, influencing their ability to manipulate societal space and optimise energy usage. This may take a countless number of explicit forms, such as getting a new job or changing their mode of transport, deciding to move house or building an extension, or even altering the consumption of material products such as clothing or electronics. Ultimately this relates to any social activity acting to implicitly optimise an individual's consumption of energy and resources at their point of end use, i.e. the domestic building in which they inhabit. As a society we ultimately facilitate such social practice using a monetary system of currency, with the above decisions therefore represented explicitly as socio-economic activity and in the economic value of space.

This argument does not therefore imply that there is a physical metabolism in the structure of the building itself, but that buildings and the wider design of space in urbanised environments represent a physical expression of society's metabolism, linking the growth of society and socio-economic networks to a physical space. The increase in energy efficiency per unit space with increasing size shown in Figure 4 are taken to represent inherent laws of optimisation in spatial design, optimally distributing energy and resources to its entire occupied space, in an analogous manor to patterns observed in biological organisms. As noted in Steadman et al., (2009), describing such a process as a "metabolism of buildings" is not accurate, as buildings do not grow and evolve in a continual process. A more broadly enveloping term for a 'metabolism of space', however, provides a more accurate characterisation for how energy usage can be tied to societal space.

Across wider society, individuals operating in society act to facilitate the relationship between the energy they consume and the space from which it is acquired through social practice and economic activity. Our motivation for manipulating societal space away from its natural form could relate to a need to optimally enhance this space to optimise the efficiency at which energy is consumed across wider society. In terms of social function, this could relate to the acquisition, transportation or ultimate consumption of energy. This idea would directly relate exponent *X* observed in Figure 4 to theories of metabolic scaling as defined by West et al., (1997). While domestic buildings operate over relatively small spatial scales, scaling relationships considered across the entire housing stock may reveal optimisation built into the inherent design of domestic space, given households represent terminal, self-contained units of end-use resource consumption from a wider network of distribution.

Development of society and growth of a global socio-economic system in a physical space can be perceived as continual. People are constantly flowing through societal space, partaking in the social interaction upon which socio-economic activity is built. There is therefore a continual change in the form and function of societal space, with a concurrent change in associated the energy use, also variable with space and time. As a result, at any given moment in time new buildings and infrastructure are being innovated, planned and constructed, while more efficient methods of social activity are being drawn up; all of which could be seen to constitute expansion in the global socio-economic 'network'. The explicit form which this innovation takes can vary significantly across society, representing itself in the spatial design of urban environments and infrastructure and the patterns of scaling associated their continual development. This relates directly to work by Bettencourt et al., (2010; 2013), who investigate scaling relationships across urban design and in the nature of socio-economic processes in developing urban environments. They begin to quantify systemic optimisations in socio-economic processes occurring across global urban environments, noting the changing nature and form of these with increasing spatial scale.

Thinking more abstractly, a socio-economic network of social interaction would not physically exist, it is purely based on an individual's perception of connectivity to others and the rest of space, and the accumulation of capital an individual acquires from this interaction. The buildings and infrastructure which facilitate this interaction represent the physical 'footprint' of this network at givens point in space and time. Therefore, the moment a buildings construction is completed is theoretically instantaneously outdated, given the continual innovation of optimal design and distribution.

Wider Interpretation and Implications

As indicated in Section 1, the scope of this thesis aims to extend itself beyond domestic buildings to assess more fundamental links between society's use of energy and space, and how each of these is perceived. Therefore, discussion is needed to assess the extent to which a sub-linear scaling relationship between energy and spatial utilisation at a domestic level can be generalised to be representative of a relationship defining societal space more widely. Generally, current conceptualisations and visualisations quantify societal space across two physical dimensions; the two-dimensional area over which it appears to extend across the earth's surface. While this is traditionally the case for convenience and simplicity of visualisation, constantly defining space in this manner acts to reinforce a perception that our society inherently defines itself by two dimensions, and similarly grows, develops and evolves in a two-dimensional manor. A growing body of research, including that developed by West et al., (1997) and Jarvis et al., (2015) discusses the dimensionality of space inhabited by society through socio-economic processing of resources. If, as discussed above, society does exhibit a spatial metabolism and metabolic scaling in its use of space, then this would suggest that a global networked distribution of resources was operating across society through three spatial dimensions, a notion currently seen as controversial in current academic thinking (Batty and Ferguson, 2011). This relates directly to the findings indicated in this thesis with energy consumed at a domestic level utilised throughout a three-dimensional spatial structure (Figure 4 and Figure 6), particularly when this energy use is attributed to space heating.

Nordbeck (1971) outlines one of several controversial, and as yet unexplained scaling relationships between population and urban area, which appears to contradict the commonly held two-dimensional view of population distributions. The sub-linear exponents given show a decline in spatial area per capita with increasing two-dimensional settlement size, giving an impression of increasing density with increased size based on current conceptualisations of spatial measurement. These exponents however lie close to the theoretical 0.66 scaling exponent that would suggest a three-dimensional population filling a two-dimensional spatial area. Batty and Ferguson (2011) review and discuss numerous scaling exponents from population-area relationships in urban environments across the developed world. They point out that the idea of a population fundamentally inhabiting a three-dimensional geometric volume is controversial, however may fail to grasp key aspects of how this dimensionality manifests itself in society. While it is true if we were to define societal space by physical Euclidean dimensions, then social space will only feel truly three-dimesnional at dense cities, where tall skyscrapers dominate the physical environment. Yet as noted in Dalgaard and Strulick (2011) and Jarvis et al., (2015), a networked infrastructure transporting mass, energy and information globally has been shown to operate through three-dimensional space, distorted by the effects of gravity predominantly constraining its distribution to the planetary surface. This form of distribution has again drawn analogous comparisons to similar distribution networks in biological organisms (West et al., 1997), following similar laws of spatial scaling. This extends the idea of a metabolic scaling relationship between space and energy use beyond domestic buildings, to more fundamental ways in which the global socio-economic system is inherently tied to some measure of physical space.

Drawing on what Fischer-Kowalski and Haberl, (1998) termed a ‘colonisation of nature’, this manipulation of biological systems, optimising their production efficiency above natural levels, represents a key conceptualisation for linking society’s metabolism to surrounding space. Numerous examples exist where ecosystem services are altered to enhance the production of natural commodities according to socio-economic demand; agriculture, fishing and forestry provide outstanding examples. By exerting influence over a given ecosystem process, manipulating its output to produce a state that could not be maintained by naturally, we are inherently incorporating this given ecological ‘space’ into society and wider socio-economic metabolism through an appropriate social practice.

Yet, continual growth and technological innovation has driven an extension of metabolism further, beyond this foundation in ecological space, pursuing resources that allow development to exceed the biological limitations of ecosystems. The mobilisation geological energy carriers and material resources by society represent an extension of socio-economic metabolism beyond ecosystems and an expansion into a non-ecological space. It is our access and ability to transform these resources that fuels contemporary consumerism and resource consumption, and drives our perception of society as a separate entity from natural ecosystems. The design, development and growth of urban systems and the wider built environment are the physical anthropogenic environment that results from this extension, inherently designed to facilitate enhanced resource flows of an extended metabolism. This allows our built environment to be conceptualised as a physical expression of a biological ecosystem where access to non-biological resources is artificially facilitated by anthropogenic socio-economic activity, and representing what can be more broadly termed a ‘colonisation of space’ by industrialised society, viewed as both a anthropogenic system and a natural entity simultaneously (Marcotullio and Boyle, 2003).

Based on this, what space we consider to be a part of the global socio-economic system, and ultimately part of anthropogenic society, is hard to define with physical spatial dimensions.

We extract and acquire our resources across a range of rates and scales of socio-economic activity, in a globally diverse range of settings. This way of thinking and conceptualising society is grounded in sociological science. Philosophical conceptualisations of societal space are put forward by sociologist Henri Lefebvre (1991), who introduced the perception of space within society being produced socially, through social interaction and practice. Lefebvre argues that the space we conceive to be inclusive within society is ultimately that which is a social product, produced through a ‘spatialisation’ of natural space. Defining space in this way focuses on the processes by which societal space is produced, how its form and socio-economic character constructs and ultimately manifests itself in the physical built environment.

Section 6: **Summary and Conclusions**

Key Findings

Key findings of the analysis and discussion of this thesis are as follows:-

- A sub-linear scaling relationship is established across the UK domestic housing stock between total household floor space area (A_{tf}) (m^2) and total household energy consumption (kWh yr^{-1}), with an apparent reduction in energy use per unit space with increased household size.

- Evidence presented indicates an influence of both geometric and social influences on the nature of sub-linear scaling, and on patterns of sub-unity scaling when the housing stock is broken down by specific household characteristics.

- Classification of the housing stock by household type highlights sub-unity patterns scaling that differ from those observed across the housing stock as a whole, emphasising the role of physical household properties on patterns of scaling.

- Classification of the housing stock by inhabitant income gives a pattern of sub-unity scaling bounded between 1 and ~2/3, indicating a potential lower limit bounded by geometric constraints.

Conclusions

There is clear political and social demand for an increased understanding of the way in which energy is consumed at a domestic level, with a need for more informed choices about our energy consuming behaviours. This relates to both our perceptions of energy consumption, both domestically and beyond, and how the use of energy is considered in the practical use and design of domestic space. This thesis ultimately aimed to challenge such perceptions, building a deeper understanding of the diversity of societal space over which energy is consumed. More specifically, this thesis aimed to assess the way in which domestic energy consumption scaled with a buildings spatial size, and to establish the origins of such scaling in the context of both physical geometric building properties and wider social influences on energy usage.

The various scaling exponents relating domestic energy use to household size presented throughout do, however, uncover potentially new revelations about the way in which energy is consumed over different domestic spatial scales. Across all scaling relationships established between household size and energy consumption in Figure 4 and Tables 1-5, exponents are shown to be sub-linear, with a decrease in energy consumed per unit space with increased household size. What changes is the extent to which this effect exhibits itself when households are reclassified by a given domestic property, with most generally bounded by exponents between ~2/3 and 1. This would suggest a lower limit on the extent to which a scale related efficiency can influence total energy consumption, bounded by the physical geometric properties of the building itself and heat loss through an exposed surface area.

The character of exponents which deviate from ~2/3 suggests the role of other factors influencing the efficiency with which energy consumption changes with spatial scale. The theories presented throughout for this deviation relate this increase in efficiency to theories of societal metabolism, drawing analogous comparisons to biological scaling observed in West et al., (1997). This line of argument would suggest an inherent optimisation of domestic energy consumption through space and time, linking the space contained within domestic buildings to that across wider society directly through the consumption of energy. Before such comparisons can be made directly with more certainty and conviction, further research is needed more clearly characterise the scaling defined by exponent *X*, given the variables used to define this relationship are not measured directly and taken for a purpose for which they were not originally intended. More discussion is also needed to establish the underlying causes of such scaling, given the results of this analysis cannot definitively identify a predominant influence of a given process on scaling, be it geometric, metabolic or otherwise.

If exponent *X* does draw direct comparisons to biological scaling, then developing such ideas more deeply will aid in understanding the inherent size related energy savings in domestic buildings at a societal scale, which have clear implications for efficient and sustainable building design. These will also deepen understanding of the inherent ways in which we manipulate societal space, both in the original design of buildings and wider urban environments and their associated distribution infrastructure. Establishing such links between space and energy may also imply a need to reconceptualise the way in which we perceive spatial utilisation in society, given that we appear use space in society just as inherently as we use energy.

Limitations

A key limitation to the analysis performed within this thesis has been the availability of data. Key datasets, including the EHS, do not ultimately provide sufficiently detailed or accurate data for defining both the spatial extent of buildings and their associated energy consumption to adequately test the stated hypothesis. Collecting this level of detail over such a large dataset presents obvious practical challenges. Measurement of the parameters required for taking this research further, such as a direct three-dimensional measurement of building volume or a recording of total building energy consumption could, however, be easily incorporated within existing surveys such as the EHS, or those measuring non-domestic spaces such as the Building Energy Efficiency Survey (BEES).

There are also limitations in the overall conclusions that can be drawn from this thesis given the scope of the data used to test the broader hypothesis and aims outlined in Section 1.

While data taken from the EHS may give a reasonable reflection of energy-space relationships at a UK domestic level, the degree to which this can be extended beyond domestic space to represent space across wider society, both nationally and beyond, is limited. In order to add justification to extending the concept of a sub-linear energy-space relationship across larger spatial aggregations, measures of energy usage over broader spatial units (such as entire towns and cities), covering a diverse range social practice and activity would need to be obtained. In contrast to domestic buildings, however, larger spatial aggregations of societal space, such as cities, have more complex definitions of what constitutes their physical geometric size (Batty and Ferguson, 2011). This makes expanding the scope of the conclusions of this thesis challenging.

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Appendices

Table 1A: Lists each of the modelled energy usage variables detailed within the EHS dataset summed to form total energy usage for each given dwelling.

EHS Variable Code	Variable label
usegas_spa	Energy used for gas space heating (kWh yr^{-1})
usegas_wat	Energy used for gas water heating (kWh yr^{-1})
usegas_coo	Energy used for gas cooking (kWh yr^{-1})
useelec_spa	Energy used for electric space heating (kWh yr^{-1})
useelec_wat	Energy used for electric water heating (kWh yr^{-1})
useelec_coo	Energy used for electric cooking (kWh yr^{-1})
useelec_lit	Energy used for lights and appliances (kWh yr^{-1})
useoil_spa	Energy used for oil/LPG/bottled gas space (kWh yr^{-1})
useoil_wat	Energy used for oil/LPG/bottled gas water (kWh yr^{-1})
usesolid_spa	Energy used for solid fuel space heating (kWh yr^{-1})
usesolid_wat	Energy used for solid fuel water heating (kWh yr^{-1})

Appendix A: Statistics for Linear regression between log transformed building main eve height and its number of floors (Figure 1).

Regression Statistics	
Multiple R	0.977
R Square	0.954
Adjusted R Square	0.954
Standard Error	1.0329
Observations	14951

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.173	0.014	12.394	0	0.146	0.201
X Variable 1	2.539	0.005	554.944	0	2.530	2.548

Appendix B: Statistics for Linear regression between log transformed total floor area (A_{tf}) (m^2) and estimated exposed surface area (A_{es}) (m^2) (Figure 3).

Regression Statistics	
Multiple R	0.996
R Square	0.991
Adjusted R Square	0.991
Standard Error	0.010
Observations	11293

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.981	0.001	860.427	0	0.979	0.983
X Variable 1	0.656	0.001	1134.982	0	0.654	0.657

Appendix C: Statistics for linear regression between log transformed total floor area (A_{tf}) (m^2) and recorded energy use (kWh yr^{-1}) for all 14,386 households (Figure 4), including Analysis of Variance (ANOVA).

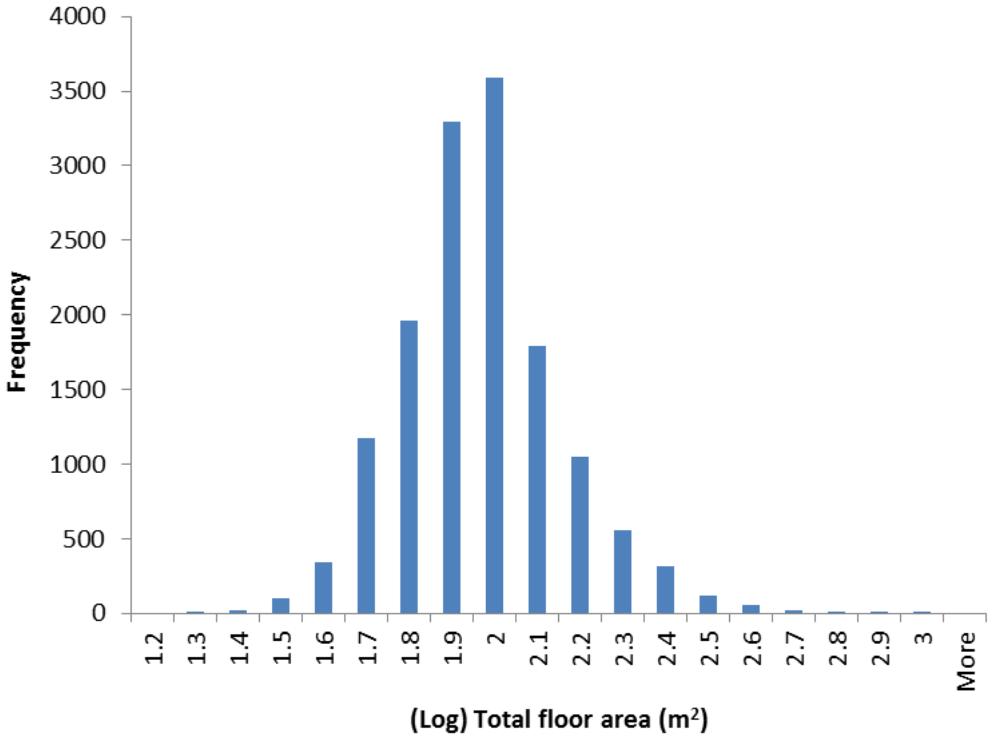
Regression Statistics	
Multiple R	0.709
R Square	0.502
Adjusted R Square	0.502
Standard Error	0.149
Observations	14386

ANOVA

	df	*Sum of Squares*	*Mean Sq. Error*	*F*	*Significance F*
Regression	1	323.455	323.455	14500.103	0
Residual	14384.000	320.865	0.022		
Total (SST)	14385.000	644.320			

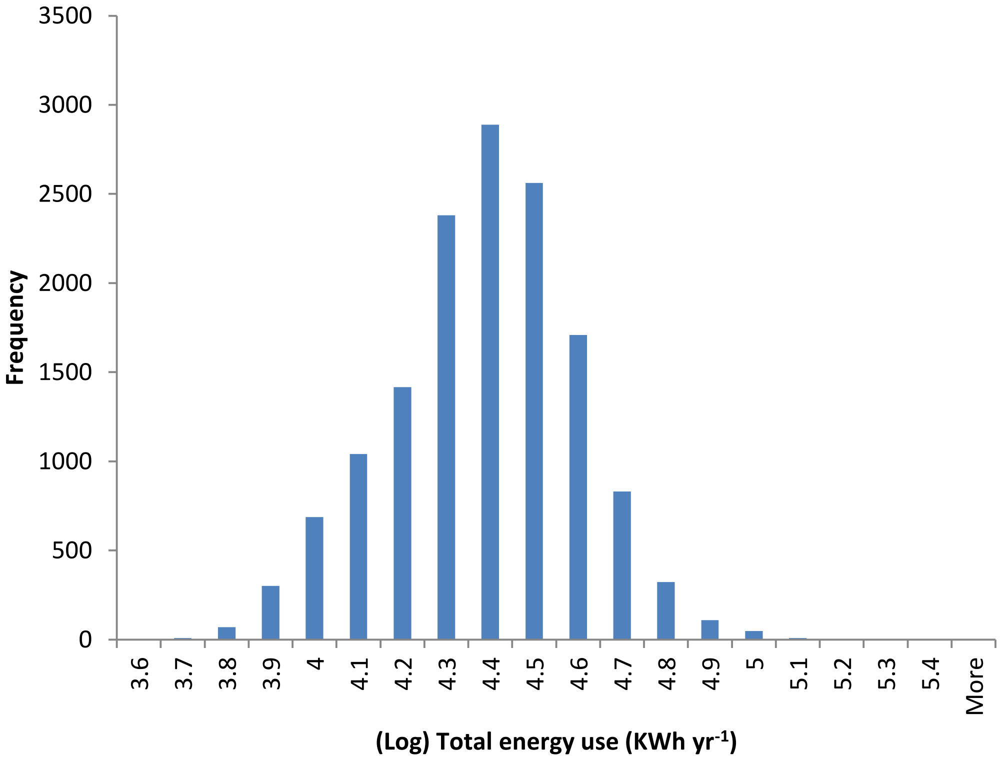
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.794	0.013	217.439	0	2.769	2.819
X Variable 1	0.803	0.007	120.416	0	0.790	0.816

Appendix D: Histogram of log transformed total floor area (A_{tf}) (m^2) data for all 14,386 households with descriptive Statistics.



Descriptive Statistics	
Mean	1.917233
Standard Error	0.001557
Median	1.908163
Mode	1.857332
Standard Deviation	0.186702
Sample Variance	0.034858
Kurtosis	1.033243
Skewness	0.50176
Range	1.79404
Minimum	1.20167
Maximum	2.99571
Count	14386
Confidence Level (95.0%)	0.003051

Appendix E: Histogram of log transformed recorded energy use (kWh yr^{-1}) data for all 14,386 households with descriptive Statistics.



Descriptive Statistics	
Mean	4.333546
Standard Error	0.001765
Median	4.346166
Mode	4.291027
Standard Deviation	0.211639
Sample Variance	0.044791
Kurtosis	0.045344
Skewness	-0.13626
Range	1.708413
Minimum	3.615135
Maximum	5.323548
Count	14386
Confidence Level (95.0%)	0.003459

Appendix F: Statistics for linear regression between log transformed total floor area (A_{tf}) (m^2) and recorded energy use ($kWh\ yr^{-1}$) for reclassified household types (Figure 4).

i) Single Unit households (Green)

Regression Statistics	
Multiple R	0.608
R Square	0.370
Adjusted R Square	0.370
Standard Error	0.132
Observations	10989

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.236	0.015	221.361	0	3.207	3.264
X Variable 1	0.594	0.007	80.312	0	0.580	0.609

ii) Purpose Built Units (Blue)

Regression Statistics	
Multiple R	0.548
R Square	0.300
Adjusted R Square	0.300
Standard Error	0.123
Observations	2866

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.969	0.031	94.859	0	2.908	3.031
X Variable 1	0.626	0.018	35.034	0	0.591	0.661

iii) Converted Units (Red)

Regression Statistics	
Multiple R	0.785
R Square	0.616
Adjusted R Square	0.615
Standard Error	0.100
Observations	528

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.112	0.042	74.895	0	3.031	3.194
X Variable 1	0.670	0.023	29.021	0	0.625	0.716

Appendix G: Statistics for linear regression between log transformed total floor area (A_{tf}) (m^2) and recorded energy use (kWh yr^{-1}), reclassified by household type (Table 1).

i) End Terrace

Regression Statistics	
Multiple R	0.523
R Square	0.273
Adjusted R Square	0.273
Standard Error	0.139
Observations	1645

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.147	0.0496	63.428	0	3.050	3.245
X Variable 1	0.645	0.0260	24.869	3.9E-116	0.594	0.696

ii) Mid Terrace

Regression Statistics	
Multiple R	0.565
R Square	0.319
Adjusted R Square	0.319
Standard Error	0.122
Observations	2793

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.097	0.034	91.179	0	3.031	3.164
X Variable 1	0.645	0.018	36.191	1.7E-235	0.610	0.680

iii) Semi-Detached

Regression Statistics	
Multiple R	0.568
R Square	0.322
Adjusted R Square	0.322
Standard Error	0.126
Observations	3989

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.188	0.028	112.929	0	3.133	3.244
X Variable 1	0.631	0.014	43.543	0	0.602	0.659

iv) Detached

Regression Statistics	
Multiple R	0.526
R Square	0.276
Adjusted R Square	0.276
Standard Error	0.133
Observations	2551

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.547	0.031	115.774	0	3.487	3.607
X Variable 1	0.449	0.014	31.190	0	0.421	0.478

v) Temporary

Regression Statistics	
Multiple R	0.198
R Square	0.039
Adjusted R Square	-0.001
Standard Error	0.120
Observations	26

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.950	0.256	15.407	0	3.421	4.479
X Variable 1	0.154	0.1560	0.990	0.332	-0.167	0.476

vi) Purpose Built Flat

Regression Statistics	
Multiple R	0.548
R Square	0.300
Adjusted R Square	0.300
Standard Error	0.122
Observations	2867

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.972	0.031	95.146	0	2.910	3.033
X Variable 1	0.624	0.018	35.033	0	0.589	0.659

vii) Converted Flat

Regression Statistics	
Multiple R	0.769
R Square	0.592
Adjusted R Square	0.591
Standard Error	0.010
Observations	499

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.101	0.045	68.859	0	3.013	3.190
X Variable 1	0.678	0.025	26.854	0	0.628	0.727

viii) Non-domestic Plus Flat

Regression Statistics	
Multiple R	0.875
R Square	0.765
Adjusted R Square	0.749
Standard Error	0.107
Observations	16

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.145	0.192	16.360	0	2.733	3.560
X Variable 1	0.650	0.096	6.760	0	0.444	0.856

Appendix H: Statistics for linear regression between log transformed total floor area (A_{tf}) (m^2) and recorded energy use (kWh yr^{-1}), reclassified by number of inhabitants (Table 2).

i) One person

Regression Statistics	
Multiple R	0.704
R Square	0.495
Adjusted R Square	0.495
Standard Error	0.152
Observations	4105

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.676	0.024	109.598	0	2.628	2.724
X Variable 1	0.849	0.013	63.455	0	0.823	0.875

ii) Two people

Regression Statistics	
Multiple R	0.654
R Square	0.428
Adjusted R Square	0.428
Standard Error	0.149
Observations	4984

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.983	0.022	132.976	0	2.939	3.027
X Variable 1	0.705	0.012	61.067	0	0.682	0.727

iii) Three people

Regression Statistics	
Multiple R	0.605
R Square	0.366
Adjusted R Square	0.366
Standard Error	0.147
Observations	2279

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.978	0.039	76.996	0	2.902	3.054
X Variable 1	0.718	0.020	36.253	0	0.679	0.757

iv) Four people

Regression Statistics	
Multiple R	0.618
R Square	0.382
Adjusted R Square	0.382
Standard Error	0.138
Observations	1927

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.114	0.038	81.641	0	3.039	3.189
X Variable 1	0.658	0.019	34.497	0	0.620	0.695

v) Five people

Regression Statistics	
Multiple R	0.662
R Square	0.438
Adjusted R Square	0.437
Standard Error	0.127
Observations	692

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.033	0.061	49.815	0	2.913	3.152
X Variable 1	0.701	0.030	23.174	0	0.642	0.761

vi) Six people

Regression Statistics	
Multiple R	0.744
R Square	0.553
Adjusted R Square	0.551
Standard Error	0.122
Observations	266

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.832	0.091	31.183	0	2.653	3.011
X Variable 1	0.805	0.045	18.073	0	0.718	0.893

vii) Seven plus people

Regression Statistics	
Multiple R	0.762
R Square	0.581
Adjusted R Square	0.578
Standard Error	0.122
Observations	133

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.922	0.119	24.508	0	2.686	3.158
X Variable 1	0.771	0.057	13.487	0	0.658	0.884

Appendix I: Statistics for linear regression between log transformed total floor area (A_{tf}) (m^2) and recorded energy use (kWh yr^{-1}), reclassified by total household income (Table 3).

i) £0-10k

Regression Statistics	
Multiple R	0.705
R Square	0.497
Adjusted R Square	0.497
Standard Error	0.155
Observations	1370

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.657	0.043	61.218	0	2.572	2.741
X Variable 1	0.869	0.024	36.787	0	0.822	0.915

ii) £10-15k

Regression Statistics	
Multiple R	0.686
R Square	0.470
Adjusted R Square	0.470
Standard Error	0.148
Observations	2765

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.629	0.033	79.941	0	2.564	2.693
X Variable 1	0.887	0.018	49.525	0	0.852	0.923

iii) £15-20k

Regression Statistics	
Multiple R	0.662
R Square	0.438
Adjusted R Square	0.438
Standard Error	0.149
Observations	2543

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.690	0.036	74.318	0	2.619	2.761
X Variable 1	0.856	0.019	44.489	0	0.818	0.894

iv) £20-25k

Regression Statistics	
Multiple R	0.647
R Square	0.419
Adjusted R Square	0.419
Standard Error	0.150
Observations	1955

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.748	0.042	64.933	0	2.665	2.831
X Variable 1	0.831	0.022	37.516	0	0.788	0.875

v) £25-30k

Regression Statistics	
Multiple R	0.641
R Square	0.411
Adjusted R Square	0.411
Standard Error	0.142
Observations	1537

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.935	0.0438	66.956	0	2.849	3.021
X Variable 1	0.738	0.0226	32.727	0	0.694	0.783

vi) £30-35k

Regression Statistics	
Multiple R	0.628
R Square	0.395
Adjusted R Square	0.394
Standard Error	0.151
Observations	1070

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.928	0.056	52.756	0	2.819	3.037
X Variable 1	0.744	0.028	26.382	0	0.689	0.799

vii) £35-40k

Regression Statistics	
Multiple R	0.651
R Square	0.424
Adjusted R Square	0.423
Standard Error	0.146
Observations	785

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.955	0.060	48.980	0	2.837	3.074
X Variable 1	0.726	0.030	23.994	0	0.667	0.786

viii) £40-50k

Regression Statistics	
Multiple R	0.639
R Square	0.409
Adjusted R Square	0.408
Standard Error	0.139
Observations	1059

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.126	0.049	64.2577	0	3.031	3.222
X Variable 1	0.647	0.024	27.033	0	0.600	0.694

ix) £50-60k

Regression Statistics	
Multiple R	0.661
R Square	0.437
Adjusted R Square	0.436
Standard Error	0.149
Observations	539

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.976	0.073	40.876	0	2.833	3.119
X Variable 1	0.715	0.035	20.404	0	0.646	0.784

x) £60 plus

Regression Statistics	
Multiple R	0.674
R Square	0.454
Adjusted R Square	0.453
Standard Error	0.153
Observations	763

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.084	0.056	54.809	0	2.974	3.195
X Variable 1	0.657	0.026	25.149	0	0.606	0.709

Appendix J: Statistics for linear regression between log transformed total floor area (A_{tf}) (m^2) and recorded energy use (kWh yr^{-1}), reclassified by date of construction (Table 4).

i) Pre-1850

Regression Statistics	
Multiple R	0.804
R Square	0.647
Adjusted R Square	0.646
Standard Error	0.124
Observations	399

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.233	0.050	65.100	0	3.136	3.331
X Variable 1	0.629	0.023	26.961	0	0.583	0.674

ii) 1850 – 1899

Regression Statistics	
Multiple R	0.768
R Square	0.590
Adjusted R Square	0.590
Standard Error	0.121
Observations	1200

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.107	0.033	94.596	0	3.043	3.171
X Variable 1	0.699	0.017	41.547	0	0.666	0.732

iii) 1900 – 1918

Regression Statistics	
Multiple R	0.738
R Square	0.545
Adjusted R Square	0.545
Standard Error	0.115
Observations	1051

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.100	0.038	81.121	0	3.025	3.175
X Variable 1	0.696	0.020	35.453	0	0.658	0.735

iv) 1919 – 1944

Regression Statistics	
Multiple R	0.648
R Square	0.420
Adjusted R Square	0.420
Standard Error	0.119
Observations	2259

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.214	0.030	105.555	0	3.154	3.274
X Variable 1	0.631	0.016	40.461	0	0.600	0.662

v) 1945-1964

Regression Statistics	
Multiple R	0.662
R Square	0.438
Adjusted R Square	0.438
Standard Error	0.122
Observations	3182

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	3.001	0.027	110.908	0	2.948	3.054
X Variable 1	0.705	0.014	49.783	0	0.677	0.732

vi) 1965-1974

Regression Statistics	
Multiple R	0.721
R Square	0.520
Adjusted R Square	0.520
Standard Error	0.137
Observations	2192

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.720	0.032	84.725	0	2.657	2.783
X Variable 1	0.822	0.017	48.684	0	0.789	0.856

vii) 1975-1980

Regression Statistics	
Multiple R	0.796
R Square	0.633
Adjusted R Square	0.633
Standard Error	0.117
Observations	1030

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.700	0.037	73.436	0	2.628	2.772
X Variable 1	0.822	0.020	42.133	0	0.784	0.860

viii) 1981-1990

Regression Statistics	
Multiple R	0.824
R Square	0.678
Adjusted R Square	0.678
Standard Error	0.121
Observations	1209

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.648	0.032	83.578	0	2.586	2.710
X Variable 1	0.848	0.017	50.449	0	0.815	0.881

ix) 1991 – 1995

Regression Statistics	
Multiple R	0.862
R Square	0.743
Adjusted R Square	0.743
Standard Error	0.107
Observations	480

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.527	0.044	56.514	0	2.439	2.614
X Variable 1	0.875	0.024	37.194	0	0.829	0.922

x) 1996-2002

Regression Statistics	
Multiple R	0.843
R Square	0.711
Adjusted R Square	0.710
Standard Error	0.101
Observations	643

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.692	0.039	69.740	0	2.616	2.768
X Variable 1	0.786	0.020	39.696	0	0.747	0.825

xi) Post 2002

Regression Statistics	
Multiple R	0.867
R Square	0.752
Adjusted R Square	0.752
Standard Error	0.096
Observations	741

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.524	0.034	74.657	0	2.458	2.591
X Variable 1	0.835	0.018	47.349	0	0.800	0.870

Appendix K: Statistics for linear regression between log transformed total floor area (A_{tf}) (m^2) and energy usage data (kWh yr^{-1}), reclassified by usage type (Table 5).

i) Space Heating

Regression Statistics	
Multiple R	0.636
R Square	0.404
Adjusted R Square	0.404
Standard Error	0.219
Observations	14386

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.295	0.019	121.876	0	2.258	2.332
X Variable 1	0.965	0.010	98.757	0	0.946	0.984

ii) Water Heating

Regression Statistics	
Multiple R	0.373
R Square	0.139
Adjusted R Square	0.139
Standard Error	0.195
Observations	14386

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.702	0.017	161.230	0	2.669	2.735
X Variable 1	0.419	0.009	48.198	0	0.402	0.436

iii) **Cooking, Lighting and Appliances**

Regression Statistics	
Multiple R	0.747
R Square	0.558
Adjusted R Square	0.558
Standard Error	0.099
Observations	14386

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.391	0.009	280.889	0.000	2.374	2.408
X Variable 1	0.595	0.004	134.687	0.000	0.586	0.604

Appendix L: Statistics for linear regression between log Exposed surface area (A_{es}) (m^2) and household energy use (kWh yr^{-1}) (Figure 5).

Regression Statistics	
Multiple R	0.602
R Square	0.363
Adjusted R Square	0.363
Standard Error	0.133
Observations	10990

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.373	0.026	92.321	0	2.323	2.424
X Variable 1	0.895	0.011	79.123	0	0.872	0.917

Appendix M: Statistics for linear regression between total floor area (A_{tf}) (m^2) per capita and recorded energy use (kWh yr^{-1}) per capita, for all 14,386 households (Figure 6).

Regression Statistics	
Multiple R	0.810
R Square	0.657
Adjusted R Square	0.657
Standard Error	0.149
Observations	14386

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.675	0.008	327.111	0	2.659	2.691
X Variable 1	0.838	0.005	165.925	0	0.828	0.848