Developing a method to assess demand side energy management opportunities from small and medium sized enterprises

Thesis submitted in partial fulfillment for the degree of

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Jeremy Rawlings

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged

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Jeremy Mark Rawlings

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Abstract

The challenges in engaging small and medium sized enterprises (SMEs) with energy reduction are widely recognised. Individual SMEs often consume little energy but collectively their energy use is significant. Electricity companies are now giving high priority to developing smart electricity grids to support a lower carbon future but a role for SMEs in this is unclear. This thesis investigates the potential for demand side management (DSM) services that a group of businesses could offer and compares this with the requirements of electricity market stakeholders. The work was supported by Reading Borough Council and considers the role that local authorities could have in bringing together groups of tenants and landlords with DSM customers.

A method was developed to estimate flexible loads from a group of office buildings, in the absence of detailed information at individual building level. Analysis of previous classifications of buildings, businesses and HVAC systems identified that heating and cooling in offices represented the largest potential load for DSM, with SMEs responsible for a significant proportion of this. A building physics approach, centred around the EnergyPlus tool, was used to simulate the temporal profiles of electricity use. Demand response potential has been quantified for four built form types, three age bands and two HVAC types.

SMEs could contribute to the DSM requirements of the System Operator or DNO in Reading but larger flexible loads are needed than currently exist with office heating and cooling. The best DSM opportunity is currently in well insulated buildings with large cooling loads. Due to the dominance of gas heating in the Reading area, the DSM opportunity is very limited but is expected to increase as more electric heating is installed. Load shifting from heating and cooling in offices could contribute to a DSM service which includes process loads and on-site generation. Achieving the greatest benefit from DSM would require close co-operation between DNOs and local businesses. SMEs face large challenges in engaging in DSM but facilitating this would be in line with local authorities' carbon reduction and business support roles.

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Abbreviations

ACH	air changes per hour
ASHP	air source heat pump
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
BaU	business as usual
BCO	British Council for Offices
BEES	Building Energy Efficiency Survey
BM	Balancing Mechanism
BRE	Building Research Establishment
BSC	Balancing and Settlement Code
BST	British Summer Time
CaRB	Carbon Reduction in Buildings
CAV	constant air volume
CBECS	Commercial Buildings Energy Consumption Survey
CCA	Climate Change Agreement
CHP	combined heat and power
CIBSE	The Chartered Institution of Building Services Engineers
CLG	Department for Communities and Local Government
CLNR	Customer Led Network Revolution
CoP	coefficient of performance
CRC	Carbon Reduction Commitment
CTF	conduction transfer function
DEC	Display Energy Certificate
DECC	Department of Energy and Climate Change
DHW	domestic hot water
DNO	Distribution Network Operator
DOAS	dedicated outdoor air system
DSBR	Demand Side Balancing Reserve
DSM	demand side management
DTI	Department of Trade and Industry
DUKES	Digest of United Kingdom Energy Statistics
DUoS	Distribution Use of System
ECUK	Energy Consumption in the United Kingdom
EngD	Engineering Doctorate
EPSRC	Engineering and Physical Sciences Research Council
EU-ETS	European Union Emissions Trading Scheme

FCU	fan coil unit
GEA	gross external area
GIA	gross internal area
GIS	geographical information system
GMT	Greenwich Mean Time
HHM	half-hour meter
HVAC	heating, ventilation and air-conditioning
IDF	input data file
IQR	inter-quartile range
LCNF	Low Carbon Networks Fund
LHS	Latin Hypercube Sampling
MEF	marginal emissions factor
NDBS	Non-domestic Building Stock database
N-DEEM	Non-domestic buildings Energy and Emissions Model
NEED	National Energy Efficiency Data Framework
NG	National Grid
NIA	net internal area
NTVV	New Thames Valley Vision
ODPM	Office of the Deputy Prime Minister
Ofgem	Office of gas and electricity markets
OS	Ordnance Survey
PCM	phase change material
RBC	Reading Borough Council
RCCP	Reading Climate Change Partnership
RL	Rating List
RTP	real-time pricing
SFP	specific fan power
SHGC	solar heat gain coefficient
SHU	Sheffield Hallam University
SIC	Standard Industrial Classification
SME	small and medium sized enterprise
SMV	Summary Valuation
SO	System Operator
SP	settlement period
SQSS	Security and Quality of Supply Standard
SSEPD	Scottish and Southern Energy Power Distribution
STOR	Short Term Operating Reserve

TMY2	Test Meteorological Year 2
TNUoS	Transmission Network Use of System
TSBE	Technologies for Sustainable Built Environments
UEA	University of East Anglia
UK GBC	UK Green Building Council
VAV	variable air volume
VOA	Valuation Office Agency
WPD	Western Power Distribution

Glossary

DNO	Distribution Network Operators own and operate the electricity distribution network that connects the high voltage transmission network to consumers. They do not sell electricity to consumers (National Grid n.d.).
DSM	'*Supporting customers to undertake short term shifting or flexing of load by changing demand patterns, increasing export or taking excess energy from a network'* (DECC 2014b).
smart grid	*'An electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies'* (European Commission 2013).
SME	*'A business with fewer than 250 employees, a turnover up to €50M or a balance sheet up to €43M'* (European Commission 2003).
SO	National Grid is the transmission System Operator for the GB electricity network. They are responsible for balancing supply and demand (National Grid n.d.).

1. Introduction

1.1 Policy Context

Life in the UK today would be almost unthinkable without electricity but its current consumption has become unsustainable. Its use has grown especially in the areas of IT and cooling in buildings (DECC 2014c). Consumption of electricity for transport and heating is predicted to grow by 2030 (National Grid 2011). According to the Department of Energy and Climate Change (DECC), most electricity generated in the UK in 2013 came from fossil fuels (MacLeay et al. 2014, Chapter 5). It is generally accepted that using these fuels is unsustainable for future generations. There is concern that this consumption is drawing on resources which are less secure because they originate from politically unstable regions of the world. These factors have led many governments to work towards decarbonisation of electricity and to support renewable energy generation. In the UK, renewable electricity is dominated by wind power, which is variable and cannot be controlled in the same way as conventional fossil fuel plant (MacLeay et al. 2014, Chapter 6).

These changes in the way that electricity is generated and consumed are likely to increase peaks in demand and require more generation capacity to balance supply and demand. These effects can be mitigated by managing demand more closely as well as supply and are leading electricity companies to develop ‘smart grids’ to ‘intelligently’ monitor and control their networks (section 2.6). Large electricity consumers have provided demand side management (DSM) services for some time. The smart grids under development by energy companies are likely to enable smaller consumers, such as small and medium sized enterprises (SMEs) to offer DSM services. For large consumers, the cost of electricity is significant and demand side services may enable them to reduce their costs or generate income. SMEs are often small electricity consumers and are unlikely to have offered demand side services. However they make up the vast majority of private sector enterprises and their total energy consumption is significant.

Local authorities are in key positions to influence carbon reduction from local organisations and may have an important co-ordinating role with SMEs (Bradford & Fraser 2008), (Barker & Jones 2013).

1.2 Background

The UK Government is concerned to reduce the country's carbon emissions, to minimise energy price rises for consumers and to maintain security of energy supply. These factors have to be managed within the regulated GB electricity market. The changes in the supply and consumption of electricity make it more important to manage electricity demand.

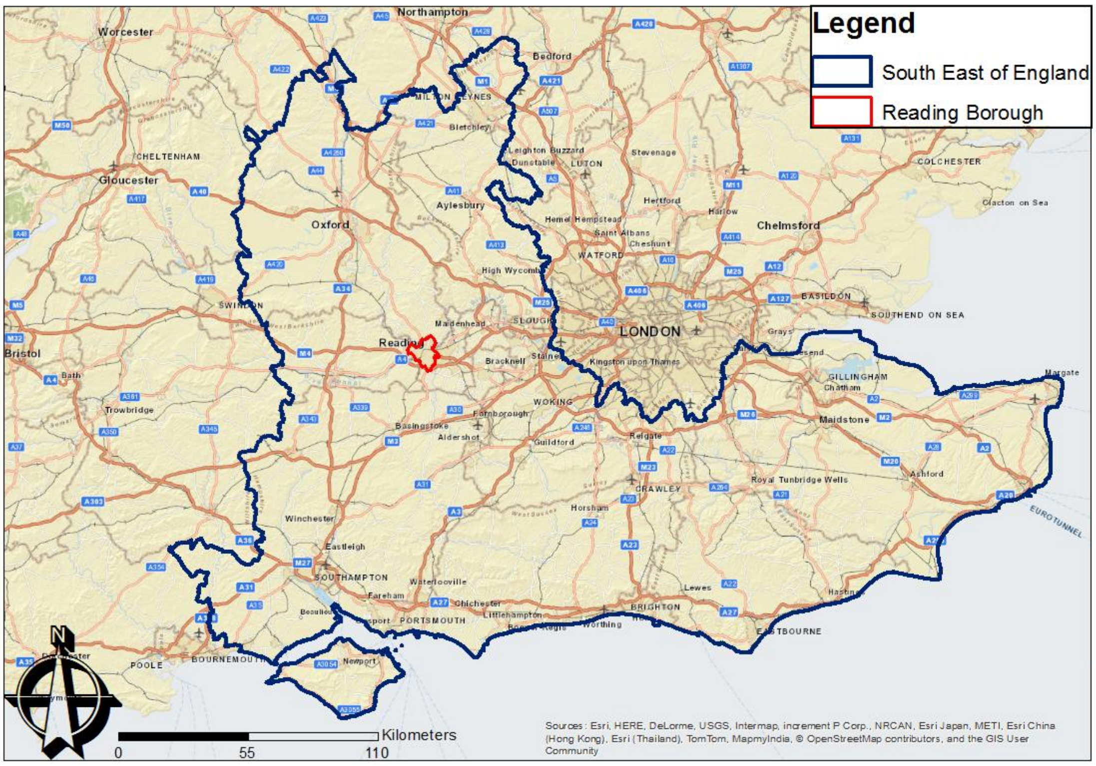
Traditional approaches to ensuring security of supply would involve substantial network investment in generation, transmission and distribution of electricity. To some extent this is essential, for example, to renew life expired infrastructure. However the need to minimise costs to consumers is translated into a need to focus investment where it is most needed. Smarter networks are being developed by electricity market stakeholders will help them understand electricity flows and plan investment. Smart grids will inform customers of their consumption in near real-time and will enable time related tariffs. Managing demand has the potential to reduce the immediate need to invest in new distribution network infrastructure. It also helps to balance supply and demand and supports carbon reduction by providing immediate feedback on the level of energy consumption and supporting distributed renewable energy installation.

SMEs make up the vast majority of UK companies. They account for over 99% of UK private sector enterprises (White 2014). An SME has fewer than 250 employees, a turnover of less than €50 million or a balance sheet of less than €43 million (European Commission 2003). There were an estimated 5.2 million SMEs in the UK at the start of 2014, an increase of 6.7% over the previous year (White 2014). This represents 60% of private sector employment and 47% of turnover. SMEs operate in every major industry category (White 2014).

Smart grids may encourage SMEs to engage in energy management and local authorities may have a role in facilitating this. Smart grids provide real-time data on energy consumption which may raise awareness of energy consumption. Energy companies will be able to offer higher tariffs at peak times to encourage demand shifting. A third party would aggregate loads from a group of businesses in order to present a useful service to the System Operator or a DNO. This may encourage consumers to save energy or invest in renewable energy. Some SMEs may be interested in opportunities to sell software or hardware to support smart grid development. There may be a role for local authorities to bring together SMEs, landlords and electricity companies to better understand the needs of all parties.

1.3 Geographical Context

Reading Borough is located in the south east of England, figure 1. It encompasses the central and older districts of the town which now extends into the Boroughs of Wokingham (south east and east) and West Berkshire (to the west). The Borough contains a higher concentration of commercial buildings than in the town overall. Reading Borough has a higher than average proportion of employment in the technology sector (Markit Economics 2013). The largest employment sectors in 2012 were ‘professional, scientific and technical’ (15%), ‘health’ (13%), ‘information and communications’ (12%) and ‘retail’ (11%) (Thames Valley Berkshire 2014).



Credit: *McCausland (2015)*

Figure 1 Reading Borough in relation to the South East of England

Reading has a high concentration of SMEs compared with other urban areas in the UK. The Centre for Cities analysed data from The Office for National Statistics (ONS) relating to the number of SMEs in the 64 largest urban areas in the UK (Centre for Cities 2014). The urban area of Reading, which was defined as the boroughs of Reading, Wokingham and Bracknell Forest, had the second highest proportion of SMEs per 10,000 population in 2013 after London. The urban area of Reading had the 5^{th} highest rate of SME 'births' in 2012. Over a quarter (26.2%) of SMEs in Reading increased their staffing level between 2010 and 2013.

Reading Borough Council (RBC) is concerned to reduce carbon emissions from all sectors in the Borough but has found it hard to engage businesses. The climate change strategy for Reading emphasises the need to work with businesses in carbon reduction (RCCP 2013a). Produced by Reading Climate Change Partnership (RCCP), its vision is:

'Reading's thriving network of businesses and organisations will be at the forefront of developing solutions for reducing carbon emissions and preparing for climate change. Low carbon living will be the norm in 2050' (RCCP 2013a).

RBC believes that the involvement of businesses, especially SMEs, is essential: 46% of the Borough's carbon footprint is due to the business sector (RCCP 2013a). RBC is encouraging businesses, especially SMEs to commit to 7% annual reduction in carbon emissions. This vision will be achieved through the delivery of eight themes. The theme for 'energy supply' covers four 'strategic priorities' which have associated actions. Theme 1, strategic priority 2: '*Introduce smart meters and energy storage solutions in Reading*' has the following action: '*Produce a model that identifies where electricity loads in buildings can be reduced at peak periods*' (RCCP 2013b). The purpose of this thesis is to achieve this objective.

SMEs are a significant part of the UK economy but they are largely unaffected by energy management and carbon reduction policies (Bradford & Fraser 2008). SMEs exist in such large numbers that their collective economic contribution and their overall energy consumption are significant. Individually this energy consumption is often small which makes it important to engage a group of SMEs to achieve a substantial reduction. Smart grids are a new technology which may provide a new opportunity to engage groups of SMEs in energy management.

1.4 Aim and Objectives

Aim:

To develop a method to quantify demand side management (DSM) opportunities from SMEs in Reading Borough

Objectives:

1. To find out what is already known about SME business activity, energy consumption and carbon reduction approaches in order to identify DSM opportunities with smart grids

2. To classify buildings and businesses in order to highlight DSM opportunities with smart grids

3. To develop a method to estimate the discretionary electrical load from a group of buildings, using simulations of individual buildings

4. To apply this approach to particular building types in Reading Borough

5. To deliver recommendations on DSM to RBC

1.5 Scope of this research

The emphasis of this research is to understand opportunities for DSM from SMEs that are based in commercial premises. A large proportion of SMEs are based at home and these are considered to be covered by domestic energy saving measures. For some SMEs, emissions from transport are larger than those from buildings. However these are dispersed and it was considered important to be able to relate the findings to property in Reading Borough. The analysis of non-domestic property aims to understand opportunities for DSM from office buildings. Although these are occupied by all types of organisations, the analysis should be applicable to SMEs.

1.6 Thesis Structure

Chapter 2 will examine the literature on SMEs and the commercial property they occupy. It will be seen that SMEs are often tenants of property with leases of comparable length to the payback periods of many energy efficiency schemes. Landlords could invest to save energy but there is little incentive for them to do so. Smart grids are introduced as a new opportunity to engage SMEs in energy management. The non-domestic building stock is extremely diverse but needs to be disaggregated in order to identify how electricity is consumed. Chapter 3 examines the literature on stock level models and on the end uses of energy within these buildings. Heating and cooling in commercial offices are identified as significant loads to be investigated for DSM. This raises topics relevant to a model, such as: ‘what floor area of office buildings have electric heating, cooling and ventilation? and ‘what is the age profile of commercial office buildings in the UK and in Reading?’. Before developing a model to quantify DSM opportunities, the reasons that GB electricity companies need these services are examined. Chapter 4 provides this background and considers what the System Operator and Distribution Network Operators would require of a DSM service from commercial offices. Literature on modelling approaches is discussed in chapter 5. The requirements for a model to represent groups of buildings are detailed. The development of the building energy model used in this research is described in chapter 6. Individual buildings were simulated and the results aggregated to represent groups of buildings. Example results are given in chapter 7. The implications of this work and the merits of the modelling approach are discussed in chapter 8. Chapter 9 details conclusions and recommendations.

1.6.1 Publications

The papers written by the author of this thesis during this research and the chapters they relate to are listed in table 1.

Paper	**Peer reviewed?**	**Chapter**
Rawlings, J; Coker, P; Doak, A and Wallis, J: *SMEs and Smart Grids: What are the Market Realities?*, in Proc. 2nd TSBE EngD Conference, University of Reading, July 2011	N	1 / 2
Rawlings, J., Coker, P., Doak, J., & Burfoot, B.: *Smart Grids: A New Incentive for SME Carbon Reduction?*, in Proc. 3rd TSBE EngD Conference, University of Reading, July 2012	N	3
Rawlings, J; Coker, P; Doak, A and Burfoot, B: *Smart Grids: A New Incentive for SME Carbon Reduction?*, Vancouver, Canada: Proc. 11th International Conference on Sustainable Energy Technologies, September 2012	N	3
Rawlings, J., Coker, P., Doak, J., & Burfoot, B.: *Do Smart Grids Offer a New Incentive for SME Carbon Reduction?*, Sustainable Cities and Society, **10**, February 2014, pp 245 - 250	Y	3
Rawlings, J., Coker, P., Doak, J., & Burfoot, B.: *The Need for New Building Energy Models to Support SME Carbon Reduction*, in Proc. 4th TSBE EngD Conference, University of Reading, July 2013	N	5 / 6
Rawlings, J., Coker, P., Doak, J., & Burfoot, B.: *A Clustering Approach to Support SME Carbon Reduction*, Building Simulation and Optimization (BSO14) Conference, London: June 2014.	Y	5 / 6
Rawlings, J., Coker, P., Doak, J., & Burfoot, B.: *A Clustering Approach to SME Carbon Reduction* in Proc. 5th TSBE EngD Conference, University of Reading, July 2014	N	5

Table 1 Conference and journal papers produced during this research

2. SME Carbon Emissions, Property and Smart Grids

2.1 Introduction

SMEs are diverse and have limited resources. The owner manager has a leading role and there is a preference for informal approaches (Vickers & Vaze, 2009). SMEs have less influence over their operating environment and less awareness of the available support (compared with large businesses). Some of the challenges facing SMEs in ‘going green’ are discussed in section 2.5. In order to understand SME energy use, this thesis looks at their premises and then some characteristics of their energy consumption. The potential energy management opportunities arising from smart grids are considered and how they relate to other carbon reduction initiatives.

SMEs are hugely diverse. Individually their energy consumption is often small though collectively this is significant because they make up the vast majority of enterprises (BIS 2014). Changes in the generation and consumption of electricity are making it more important to manage demand. Local authorities may have a role here in co-ordinating many SMEs, landlords and energy companies in energy management. A local authority is in a key position to influence environmental behaviour in their area (Barker & Jones 2013). Energy management by SMEs would support the local authority’s carbon reduction agenda and economic development.

This chapter examines what is known about SMEs, the premises they occupy and the energy they consume. This raises questions such as: To what extent are SMEs aware of their own energy consumption? What business reasons are there for SMEs to use less energy? A number of existing carbon reduction measures are discussed. Smart grids represent a new development which will facilitate energy management and support carbon reduction. This may provide incentives for SMEs to engage in energy management.

2.2 Commercial Property

Non-domestic property in the UK accounts for approximately 19% of total CO_2 emissions (Hinnells 2008). Commercial office and warehousing space is constructed at 1 to 2% per year, (Ravetz 2008). BRE calculate that in 2050, 60% of commercial floor space will have been constructed prior to 2010 (MacKenzie et al. 2010). This emphasises the need to focus on refurbishing existing buildings in order for the UK to meet its carbon reduction targets

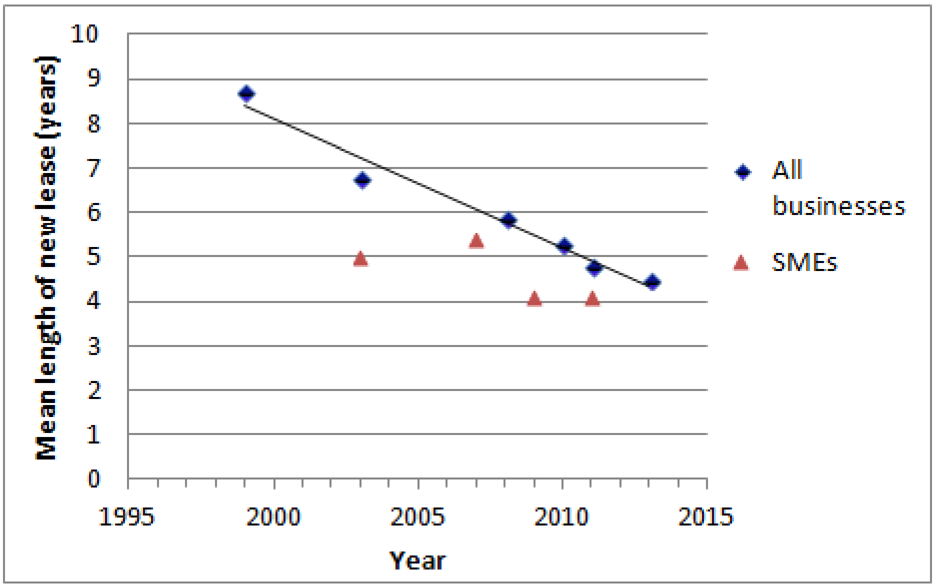
The CO_2 emissions from commercial property remained broadly unchanged from 1990 to 2008 (Committee on Climate Change, 2008; Committee on Climate Change, 2010). During 2009, indirect emissions (from electricity) fell by 14% and direct emissions (from fuel for heating) fell by 10%. This is understood to be largely due to the recession. Heating, lighting and ventilation account for 80% of the emissions related to the building fabric, (Carbon Trust 2009).

A significant proportion of SME CO_2 is unregulated by existing legislation. The Carbon Reduction Commitment (CRC), Climate Change Agreements and the EU Emissions Trading Scheme (EU ETS) control the emissions of the largest energy users. Most SMEs are below the thresholds of these measures. Enterprise Nation estimate that over 50% of SMEs or 2.8 million businesses are based at home (Ruseva 2014). Most (88%) of the home businesses surveyed were sole traders. The energy used by these organisations is regulated by domestic energy efficiency measures (such as Green Deal and local authority insulation schemes) and so they are excluded from this evaluation. This thesis considers SMEs based in commercial premises.

The culture in the [construction and development] industry is often risk-averse. (Government Office for Science 2008, p.126). This is partly because the capital is often invested by groups requiring steady growth and dividends. Nearly one fifth (19%) of owners are UK insurance companies and pension funds responsible for long-term investments (British Property Federation 2014). Overseas investors increased their share rapidly substantially between 2003 and 2013 to 24%, although their ownership tends to ebb and flow in relation to global patterns of economic activity. The prestige end of the property market (occupied by large ‘blue chip’ companies) tends to be dominated by financial institutions (Scrase 2001). This leaves the public sector and smaller private sector landlords to own (higher risk) properties that SMEs occupy.

More than half of commercial property is rented and the standard lease terms act as a dis-incentive to investment in energy saving improvements. 56% of UK commercial property by capital value was rented in 2013 (British Property Federation 2014). One reason that SME CO_2 remains high is the complex interaction of commercial landlord, agent and tenant (Carbon Trust, 2009), (Axon et al. 2012). This often creates a ‘circle of inertia’: if the landlord were to invest in the building, the tenant would benefit but the landlord would not be able to recover the cost under a standard lease.

New leases have become shorter and are now comparable with the reported payback periods of energy saving projects. The mean length of new commercial leases decreased from 8.7 years in 1999 to 4.5 years in mid 2013 (figure 2) (British Property Federation 2014). 81% of all new leases are now for 5 years or shorter. Leases taken out by SMEs are shorter and have decreased slightly from 5 years in 2003 to 4.1 years in 2011. Some businesses, typically smaller ones, work from serviced accommodation. This flexible approach is associated with short tenure. From 2013 to 2014, the mean license length in the UK was 9 months (OfficeBroker 2014). According to the Green Investment Bank, the payback period of non-domestic energy efficiency schemes in the UK was just under five years in 2014 (Jeffries et al. 2015).



Source: *British Property Federation (2010 to 2014)*

Figure 2 Length of new leases

2.3 SME Energy Consumption

It is difficult to estimate the energy consumed by SMEs. No energy data organised by sector and size is publicly available. The published estimates of SME carbon emissions are difficult to verify. The Impact Assessment for smart meters published by DECC states that 2.14 million electricity meters in smaller non-domestic premises will be replaced (DECC 2014e). The estimated usage through each meter is 17,400 kWh. Assuming that all of these are supplying SMEs, SME emissions are 47.2 $MtCO_2$/yr. This excludes home-based SMEs and those that pay indirectly, such as through the service charge. Databuild, in a report for AEA, estimate that the SME sector contributes 20 – 40 $MtCO_2$/yr, (Fawcett 2010). This wide variation is indicative of the lack of data. A report by AEA for DECC proposes 49 $MtCO_2$/yr based on a survey of 400 companies that are not ‘constrained’ by existing policies such as the Emissions Trading Scheme (Forster et al. 2010).

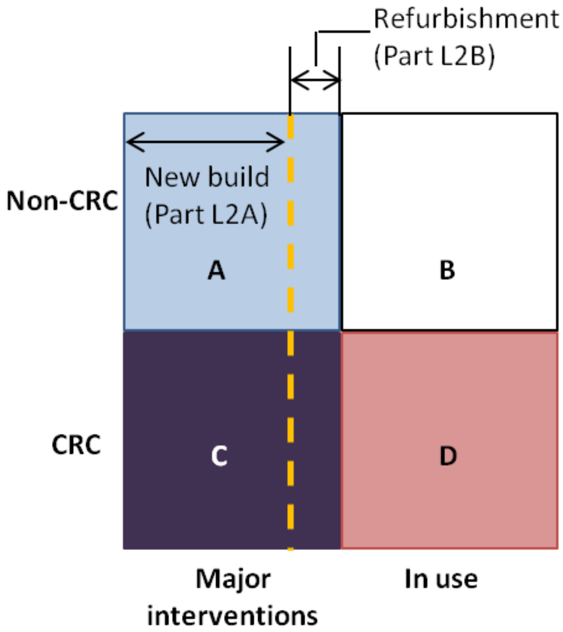
SME energy bills are often low, so cost-effective energy savings are small. For many SMEs, especially those based in offices, energy represents only 1-2% of costs (The Carbon Trust, 2009, p.9). In some cases, energy spend is less than 1%. This was the case for between a quarter and a third of businesses surveyed in South East England in 2006 (BusinessLink 2006). The Federation of Small Businesses (FSB) argue that SMEs have the potential to save 20% of their energy, compared with around 8% for large companies (Wood & Caro, 2010, p.4, citing Carbon Trust research). However this was based on data from companies that spent at least £50k/yr on energy. Defra evaluated the impact on SMEs of saving 15% on energy bills. Allowing £500/day for staff costs to implement savings, they found that enterprises with fewer than 10 staff, would save the equivalent of 0.2 person days per year. This was based on a typical energy spend of £600/yr. For enterprises with 11 to 50 employees, saving 15% was equivalent to 1.4 person days per year, (Defra 2006, p.13).

Some SMEs pay for energy indirectly (such as through their rent or service charge). A survey of 400 SMEs (published by DECC) found that 14% of sites pay for both gas and electricity indirectly (Fawcett 2010). 43% of sites pay for electricity directly to their supplier.

SMEs are likely to pay a higher unit charge for energy than large consumers. According to DECC, ‘small’ non-domestic consumers paid 15% more per kWh than the mean price for electricity and 37% more for gas during 3rd quarter of 2014 (DECC 2014d). ‘Small’ consumption was defined as 20 to 499 MWh/year of electricity and 278 to 2,777 MWh/year of gas. ‘Very small’ consumers with even lower usage paid at significantly higher unit rates. SMEs may be unable to afford ‘hedge’ against price volatility by purchasing energy in advance at lower rates.

2.4 Carbon Reduction Policies

The Carbon Trust suggests that cost effective carbon savings of 15% can be achieved in existing buildings. For non-domestic buildings (excluding industrial process emissions), this was estimated to be 26 $MtCO_2$/yr in 2005 (Carbon Trust 2009, p.87). This can be divided into businesses affected by the Carbon Reduction Commitment (CRC) and those not and buildings that will receive major interventions (construction and retrofit) and those in use figure 3. Each of these categories is roughly 6-7 $MtCO_2$, represented by the four quadrants. Most SMEs occupy quadrant B, which is largely unregulated by carbon reduction policies.



Source: *Carbon Trust (2009)*

Figure 3 Relationship of existing carbon reduction policies to sectors

A number of policies aim to reduce CO_2 emissions from business but these have limited relevance to SMEs. Table 2 lists some existing incentives (Carbon Trust 2009; DECC 2011b; Carbon Trust n.d.; HMRC, 2010). Both buildings and occupants must be targeted. Some organisations have used ‘Green Leases’ whereby the landlord and tenant agree mutual obligations (such as sharing of energy data) in order to minimise the environmental impact of the building (Pinsent Masons 2012). A new opportunity arises with the proposal for smart meters, which is discussed in section 2.6.

Table 2 Carbon Reduction Policies Affecting Businesses

Existing Buildings – Refurbishment and New Build	
Building Regulations	Part L specifies minimum standards for new build or renovation.
DECs	Identifies the actual energy consumed in public buildings during the previous year.
EPCs	Shows the expected energy consumption of the building.
SMEs and Landlords	
CRC	Mandatory cap for large energy users. Only likely to affect SME landlords.
EU Emissions Trading Scheme	Mandatory 'cap and trade' scheme affecting energy intensive industries (such as electricity generation, vehicle production and glass making).
Climate Change Levy	A tax on business energy from fossil fuel sources. Charge is levied by supplier. Domestic supplies are excluded.
Carbon Trust loans	Interest-free loans, repaid through energy savings over four years.
Feed-in Tariff	Payment for electricity generated by small renewable systems.
Green Deal	Planned measure to allow businesses to invest in energy efficiency measures and re-pay through their energy bills.
Enhanced Capital Allowances	Tax break for investing in energy efficiency measures.

Source: *(Carbon Trust 2009;* (DECC 2014a)*; Carbon Trust n.d.; HMRC, 2010)*

2.5 Challenges SMEs face in Carbon Reduction

Table 3 Top barriers to energy saving reported by SMEs

	Lloyds Bank	**FSB**	**NAO**
Cost	1	1	1
Lack of time	2	3	2
Impact of recession	4		
Business is too small		2	4
Bureaucracy		4	
Funding not available	3		3
Sample	539 SMEs with turnover up to £15M	1700 FSB members	580 recipients of CT loans
Publication date	October 2010	December 2007	November 2007

Source: *(Lloyds Bank 2010), (Connell 2007), (National Audit Office 2007)*

A number of reports analyse the challenges faced by small businesses on the path to greater environmental responsibility. These cover a broad range of topics, including social responsibility, waste reduction and energy efficiency. Table 3 lists the top four barriers given by small businesses in three surveys and shows that cost was the top factor.

Lack of time and 'business is too small' (interpreted to mean: 'lack of resources') were high on the list. This also means that an owner/ manager considers that their impact is so small that there is no benefit to try to reduce energy as they are already a very light user. FSB noted that environmental legislation does not allow for the huge variation in SMEs and consequently imposes an unnecessarily large burden. 40% of the respondents in their survey had implemented at least one energy efficiency measure. The National Audit Office (NAO) survey of companies who had received Carbon Trust loans, is likely to be biased towards larger organisations and the public sector. Lloyds Bank found that only 38% of SMEs had sought to analyse their environmental risks.

Vickers and Vaze note the following characteristics of SMEs that are likely to affect any change (Vickers & Vaze 2009, p.11):

- Limited resources in terms of finance, access to capital, knowledge, skills.
- The dominance of the owner manager which can restrict the development of the business.
- Preference for informal styles of management.
- Less ability to influence their operating environment compared with larger businesses.
- Low levels of awareness of available advice and a reluctance to access it.

They add: *the sheer numbers and "low visibility" of smaller enterprises pose a particular challenge for those who wish to assist or otherwise have a positive influence on their growth and behaviour*. (Vickers & Vaze 2009, p.12).

2.6 Smart Meters in Great Britain

The UK Government plans to replace electricity and gas meters in all homes and small businesses in Great Britain by 2020 (DECC 2014g). This supports the Government's carbon reduction objectives by encouraging investment in renewable energy and energy efficiency (DECC 2014e).

Approximately 53 million electricity and gas meters are being replaced with ‘smart’ meters which provide near real-time information on energy consumption (DECC 2014e). This is expected to result in a reduction in energy demand and a shift in demand away from peak periods. Smart meters will also facilitate local renewable energy supply into the electricity grid.

The term ‘smart meter’ is used very loosely in the literature to describe an ‘intelligent’ meter which can communicate, usually bi-directionally, with the energy supplier (DECC 2013b). Meters that comply with the Government’s Smart Meter Equipment Technical Specification (SMETS) will store energy consumption data, enable two-way communication with supplier and communicate with devices connected to a home area network (DECC 2014f). This will facilitate DSM from time of use tariffs or load shedding and enable ‘smart’ appliances to be scheduled remotely. The smart meter will record electricity exported from renewable energy systems.

Each smart meter collects data on energy use which is displayed for the benefit of the consumer and transmitted to the energy provider. This paves the way for bespoke energy advice and time of day tariffs. It replaces estimated bills and the requirement for regular meter reading with accurate bills. Smart meters are anticipated to facilitate greater competition by smoothing the process of changing suppliers. Energy providers will receive data on consumer behaviour at far higher granularity which will help them focus network investment. It also informs them immediately of supply failures. (DECC 2011b). The smart meter roll-out includes infrastructure to enable:

- Energy companies to communicate with their meters via a wide area network.
- The display of energy consumption in a user accessible format.
- Communication between the energy meters in the customer premises and potentially smart enabled devices and micro-generation systems.

For businesses, energy consumption data may be displayed on an in-home display (IHD) or via internet based applications (DECC 2014e). The smart meter will communicate with smart enabled appliances, which can be switched off or delayed by signals from the meter. In a business this might consist of air-conditioning or ventilation. The smart meter roll-out will affect all businesses with unrestricted electricity meters (profile classes 3 and 4) or gas consumption of less than 732 MWh/yr (DECC, 2011a; Elexon, 2008). DECC estimates that 2.1 million non-domestic electricity meters will be changed (DECC 2014e). DECC proposes that the provision of smart meters and data will reduce non-domestic electricity consumption by 2.8%.

The Government proposes that the smart meter roll-out will facilitate the development of smart grids which will enable the energy companies to manage the (electricity) distribution system more efficiently (DECC 2014e). Smart grids are described by The European Technology Platform SmartGrids as: '*electricity networks that can intelligently integrate the behaviour and actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.'* (European Commission 2013). A smart grid is a collection of innovative technologies that will create a more responsive and integrated electricity network. Other pressures on electricity supply companies that account for their interest in smart grids include:

- An increasing proportion of electricity is being generated by wind power. (At least 30% of electricity is expected to come from renewable sources by 2020 in the UK Renewable Energy Strategy) (DECC 2009).

- Over 8 GW of coal and gas generating capacity was closed or 'mothballed' during 2013/14 and a further 10 GW of capacity is expected to close by 2020 (DECC & Ofgem 2014). These closures are to avoid plant upgrade costs needed to comply with the Large Combustion Plants Directive (European Parliament 2001) and the Industrial Emissions Directive (European Parliament 2010). Around 3.9 GW of nuclear capacity will close by the end of 2020 for safety reasons (DECC & Ofgem 2014).

- Additional demand may be realised from the take-up of electric heat pumps and electric vehicles. The effect of this is likely to arise after 2030 (National Grid 2011).

The high voltage transmission network is actively managed but the lower voltage distribution network is largely unmanaged. It is thought that smart grids will integrate all parts of the network to enable active management of the customer and distribution network layers.

It is not yet understood the extent to which smart meters will facilitate engagement with SMEs in energy reduction. Darby looks at the scope for smart meters to engage householders and notes interest in simple messages about energy costs and direct comparisons over time (Darby 2010). She argues that more effort is required to define what information is offered to the end user and in what format. For smart meters to achieve demand reduction, will require a clear focus and customer support.

2.7 Local Authorities, SMEs and Smart Grids

Local authorities are required to strive for CO_2 reduction in their areas, encompassing all organisations. Since the vast majority of businesses are SMEs, they have to contribute to carbon reduction and energy saving. Their sheer numbers mean they cannot be ignored but their diversity and small size require a variety of approaches. Estimating the CO_2 emissions from SMEs is difficult because of the lack of published data. One approach is to identify the data relating to business premises. Commercial property CO_2 fell slightly during 2009, most likely due to the recession. Roughly half of SMEs are based at home, so their business CO_2 is never considered. Individually this will be small though collectively this could be significant. Some SMEs occupy premises where the price of energy is not visible. This includes enterprises in serviced accommodation where the license period is typically less than one year. The trend is for commercial leases, especially those for SMEs, to shorten. This reduces any incentive for tenants or landlords to invest in fabric-related energy saving measures. Property owners want low risk investments that provide a steady return to pension or other investment funds.

The research described above highlights the energy saving potential for SMEs. For many, especially those in the service sector, the energy that could be readily saved, is a tiny sum. This does not compare well with the staff costs required, especially where many actions have to be repeated daily (such as switching off lights and computers). SMEs themselves recognise cost and lack of resources as key constraints in the carbon saving journey.

There are several existing carbon saving incentives. To be effective, these need to address the buildings and the tenant SMEs. As figure 3 shows, SMEs are largely unaffected by the CRC and Building Regulations.

Smart meters present new opportunities for SMEs to engage in cutting CO_2 emissions. This is made possible through increased awareness of energy usage, time of day tariffs, possible financial incentives to reduce loads at peak times and measurement of renewable electricity. One example is Scottish and Southern Energy Power Distribution's (SSEPD) Thames Valley Vision Project which aims to: '*revolutionise electricity distribution networks in and around Bracknell'* (SSEPD 2012b). Renewable energy systems and smart grid infrastructure will provide more data on electricity flows and engage businesses and households.

2.8 Conclusion

SME energy consumption is collectively significant but for many companies is low. Many SMEs are largely unaware of their energy costs which are either hidden or small and overlooked. The cost effective energy saving for a small company (calculated in £) equates to a small amount of human resource but the reward from the saving is trivial.

A number of existing policies were reviewed but SMEs are mostly unaffected. Either large organisations or large consumers are targeted. Other measures that relate to building refurbishment apply infrequently or offer no direct benefit to the landlord who bears the expense. Conflicting interests between landlord and tenant create a '*circle of inertia*' which obstructs building refurbishment.

The development of smart grids may offer a new opportunity. This offers the potential for SMEs to engage in energy management through demand side tariffs and greater energy awareness. These present opportunities to make or save money through time-shifting of discretionary loads. In order to understand this potential, the non-domestic building stock is analysed.

3. Analysis of the Non-domestic Building Stock

3.1 Introduction

Chapter 2 highlighted that SMEs individually are often small energy consumers though significant collectively. Energy management is often a low priority due to the low or unknown cost of energy. The opportunities to make or save money provided by demand side management (DSM) facilitated by smart grids may offer new incentives to reduce demand. The low level of consumption from individual SMEs points to the need to aggregate demand across groups of businesses. An understanding of how energy is consumed (by end use and with respect to time) is needed to identify DSM opportunities. The roles of the key parties in the electricity industry and their interest in DSM are examined in chapter 4.

This chapter aims to classify buildings and businesses in order to highlight opportunities for DSM with smart grids. Previous studies that classified non-domestic buildings and business activities for the purpose of energy efficiency are reviewed (section 3.3). One of the challenges this highlights is that of separating annual energy consumption into end use components, which is a first step in calculating the potential for DSM. Analysis of publicly available data calculates a breakdown of electricity by business activity type and end use for SMEs (section 3.4). This calculation of annual demand highlights heating and cooling in offices which are investigated for DSM potential in the modelling work described in chapter 6. This is developed further in section 3.5 which considers additional aspects required for this model. These are thermal mass, the relationship of building age to thermal envelope properties, HVAC system type and a breakdown by floor area for Reading.

3.2 Scope of Analysis

In order to quantify DSM opportunities, it is necessary to disaggregate building energy into the factors that affect consumption. Time profiles of demand are required which should be disaggregated into separate end uses in order to determine the load shifting opportunity. Since SMEs are often small energy consumers, many loads will have to be aggregated in time. These may be from buildings that are in close proximity, such as on a business park or widely separated. In reviewing building energy models at the district scale, Bourdic & Salat (2012) state that energy consumption in buildings is affected by: climate, urban context, buildings, systems, occupants and energy performance. The authors explain that no model is able to cover all aspects. In the context of SME DSM, the factors affecting energy consumption in buildings are understood as shown in figure 4. Climate is an input via the weather file in the model. 'Urban context' maps to neighbourhood factors, which are shading and solar radiation on buildings. This factor is excluded from the model due to its site specific nature (section 8.3.1). 'Buildings' and 'systems' are mapped to 'built form' and 'HVAC'. 'Occupants' relates to 'business activity and schedules' and 'energy performance' to system types and ratings included in the model. 'Building thermal mass' is an additional factor though this is implicit in the modelling tool. These factors affect building energy consumption which in some way affects the load that can be shifted. This indirect or uncertain relationship is indicated by a broken line. The review of classifications (section 3.3) considers built form, business activity, HVAC and age.

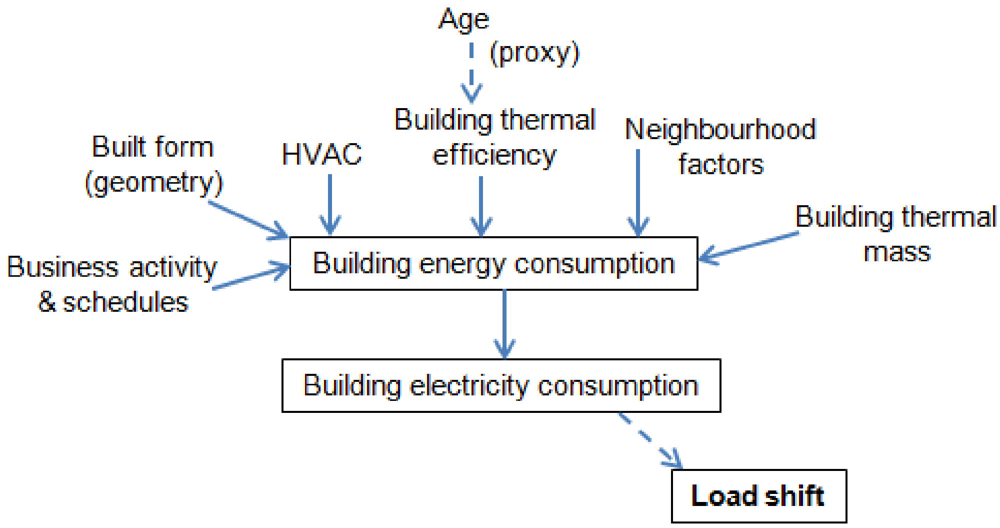


Figure 4 Relationship of factors affecting building energy consumption, based on (Bourdic & Salat 2012)

Some key terms need to be defined in the process of classifying non-domestic buildings. These could be summed up as: '*What constitutes one non-domestic building?'* and '*How is business activity related to building type?'* (Bruhns et al. 2000). Non-domestic property is more diverse than residential. There are many types of physical structures (such as sheds and halls) and the activities these buildings encompass are hugely varied. Understanding existing building types is a pre-requisite to characterising their energy consumption and the opportunities for carbon reduction.

'A building encloses space which is accessible and useable for some human activity' (Bruhns et al. 2000). In this context, this is limited to structures that require energy input (such as heating), are '*reasonably permanent'* (to include 'Portakabins' but not tents) and above a '*certain size'* (ruling out telephone boxes). '*Non-domestic'* refers to buildings that are not private residential accommodation. Bruhns et al. (2000) included residential homes, homeless hostels and guest houses but not holiday letting. This includes premises that provide accommodation as part of a business but not private dwellings. Buildings occupied by businesses that operate from home are excluded.

There is a loose relationship between building structure and the activities enclosed (Bruhns et al. 2000). Many building types can contain office activities. A physical shed can contain a warehouse, factory units or offices. Frequently a building provides space for more than one business or a mixture of businesses and dwellings, such as a block of shops with offices or residential apartments above. Each premise could contain a different business activity, with a different energy use profile. A '*premise'* is the accommodation that '*one business occupies exclusively and consists of part of a building, the whole building or many adjacent buildings'* (Bruhns et al. 2000). This is equivalent to '*hereditament*' used to record property in the Valuation Office Agency's (VOA) databases.

In England and Wales, the VOA record details of property (domestic and non-domestic) for taxation purposes (Bruhns 2000). This makes the VOA the most comprehensive source of property data for non-domestic buildings. The VOA categorises property, by '*hereditament'*, so it makes sense to record property in a compatible manner. The legal definition of 'hereditament' does not describe its physical extent (Parliament 1967), (Parliament 1988b). VOA explain that a hereditament '*must be capable of separate occupation*' and '*there can only be one rateable occupier of a hereditament*' (VOA 2006). This may consist of two or more adjacent properties providing they are in the same rating area.

3.3 Previous classification of non-domestic buildings and businesses

This section reviews previous research on classification of buildings and businesses.

3.3.1 Non-domestic Building Stock Database (NDBS)

During the 1990's the Government sponsored the development of the NDBS. Its' purpose was to understand the non-domestic building stock better, in order to inform policy relating to CO_2 reduction (Steadman, Bruhns & Rickaby 2000). The NDBS classified property and gathered statistics on numbers, types and floor areas and on how energy was consumed.

Four main data sources were used:

- External surveys of 3350 properties in four English towns carried out between 1989 and 1992 (Brown et al. 2000). The construction, fabric, envelope and activities were recorded. The floor areas, flat roof areas and other dimensions were calculated.

- Internal surveys of 700 properties mainly in the same four towns, in the 1990's which aimed to build a comprehensive picture of energy consumption by recording equipment loads and usage profiles (Mortimer et al. 2000).

Data from VOA were used to scale the above data to represent the national stock (Steadman, Bruhns & Rickaby 2000). The VOA records all non-domestic property in England and Wales that is subject to rates. A few types of property are exempt from business rates, such as, property in enterprise zones, agricultural buildings and places of worship (Parliament 1988a). These are not assessed for rateable value (VOA 2010b).

The VOA records consists of the Summary Valuation (SMV) and the Rating List (RL), (VOA 2010a). The SMV is a database that contains detailed data on shops, offices, factories and warehouses in 1.3 million hereditaments. The RL covers all 1.7 million hereditaments (with address, valuation and a brief description) (Bruhns 2000).

The classification of buildings was simplified by separating each structure into its components, consisting of primary parts and '*parasitic'* structures (Steadman, Bruhns, Holtier, et al. 2000). Since this breaks the building down into shapes, it is possible to account for each component of a building, which enables the relationship between built form and energy consumption to be understood more clearly. The classification of built forms was based on plan depth (narrow or deep) and how space was used (cellular or open plan) (Steadman, Bruhns, Holtier, et al. 2000). The authors developed six 'principal built form types': 'daylit (sidelit) cellular', 'artificially lit cellular', 'daylit hall', 'artificially lit hall', 'daylit open-plan' and 'artificially lit open-plan'. The most common type observed by the authors was 'sidelit cellular' (type CS) which accounted for nearly 40% of the buildings stock. 'Composite sidelit around artificially lit open-plan' (CDO) represented nearly 20% of the non-domestic floor area. 'Open plan artificially lit multi-storey space'

(OA) and ‘sidelit open plan’ (OA) represented around 8.5% of floor area. The remaining types consisted of ‘halls’ and ‘sheds’ which are used for warehouses, large retail stores and entertainment venues such as cinemas. Office buildings could be represented by four types (OD, CS, OA and CDO), listed in table 4. If these four types are scaled up to 100% to represent only office buildings, the proportions in the right hand column are observed.

Table 4 Built form types described by Steadman et al. (2000)

Type	Proportion in stock sampled	Proportion in office buildings
OD	2.90%	4.32%
CS	39.17%	58.40%
OA	5.50%	8.20%
CDO	19.50%	29.07%
	67.07%	**100.00%**

Statistics of floor areas and numbers for most building types, classified by activity in England and Wales were generated for 1994. Data on the extent of air-conditioning and analysis on a regional basis were identified.

This work is of particular interest because property types and floor areas were combined with energy consumption, broken down by fuel and end use. This floor area and energy data were used in the Carbon Reduction in Buildings Project (CaRB) to compare with data published in the Digest of UK Energy Statistics (DUKES) (Bruhns et al. 2006). DUKES gives totals of energy delivered by utility companies (top down). This achieved good correlation.

3.3.2 Non-domestic buildings Energy and Emissions Model (N-DEEM)

N-DEEM was developed by the Building Research Establishment (BRE) using data from NDBS to model energy use in non-domestic property and carbon reduction scenarios (Pout 2000). It aimed to disaggregate the data according to six parameters: activity of the building user, construction (materials and structures), age of premises, size band, end use of energy and fuel. The activity of the occupant is key since this determines the purpose of the energy consumption. The building age and size were used as proxies for construction data as this was not generally available. Since N-DEEM used VOA data, energy consumption was determined for premises but the relationship to complete buildings was unclear (Pout 2000). N-DEEM did not take account of differences in building fabric but applied energy use indices to floor areas. Analysis by N-DEEM was used to generate the Energy Consumption in the UK (ECUK) data, published by DECC (DTI 2002). The floor area data available in developing N-DEEM only covered England and Wales (Pout 2000). This was extrapolated to cover the UK by multiplying by the ratio of UK population to that of England and Wales.

3.3.3 The National Energy Efficiency Data framework (NEED)

NEED aims to create a central framework for recording information on the entire building stock in Great Britain (Neffendorf et al. 2009). It aims to monitor changes in energy use and focus resources to reduce consumption in individual sectors. It will identify the effect of more accurate demand side data (such as from smart meters) on managing supply side problems. NEED collates and links several data sets (Neffendorf et al. 2009, pp.11-14):

- Physical footprints of buildings linked to addresses
- A national property address database which correlates with the VOA rates data
- Non-domestic rates data which contains rented floor areas
- A national Government register of business addresses, linked to data on the number of employees, turnover and activities
- Gas and electricity meter point data supplied by Xoserve and Gemserv

A pilot study in Bristol highlighted the difficulty of matching data from energy meters to premises data (Bruhns & Wyatt 2011).

3.3.4 Current Building Stock Projects

The '*Building Energy Efficiency Survey*' (BEES) aims to improve the available data on non-domestic building energy consumption through energy surveys (DECC 2013a). Telephone and site audits are being used to collect bottom-up energy consumption data for comparison with estimates from energy bills. A pilot study of 862 sites reported poor correlation between energy estimates for individual sites but similar total energy consumption data.

The '*4M Project'* aims to develop a methodology to determine the carbon footprint of UK cities (Lomas 2011). Taking the city of Leicester as a case study, the project will calculate the carbon emissions from natural and anthropogenic sources. Carbon emissions from buildings, transport, soils and vegetation are being mapped. The intention is to create a strategy which will inform policy makers and demonstrate the impact of different interventions. Each non-domestic building is represented using a simplified approach which calculates the external heat losses and gains for that individual building. This combines premises data from VOA with building level data in the Local Land and Property Gazetteer and data on building heights. It is expected that this model will represent the CO_2 impact of energy saving and renewable energy measures.

3.4 Analysis of SME Electrical Loads

3.4.1 Method of Analysis

This above research provides benchmarks for energy use and shows the challenge of identifying potential loads to time-shift. Electricity grid de-carbonisation will bring new opportunities for consumers to contribute to supply management and carbon reduction. Smart grid technology provides pricing incentives to engage customers in managing their consumption. This section attempts to identify end use categories from publicly available data where smart grids could shift demand away from peak periods.

AEA estimated the energy consumed by '*organisations whose energy use is not covered by current binding UK energy efficiency or carbon abatement policy'* (Forster et al. 2010). AEA referred to these organisations as the '*unconstrained'* sector. '*Unconstrained'* energy consisted of the '*energy use in non domestic buildings and industrial activities that is not covered by the EU ETS, CCAs or CRC*'. The energy associated with these carbon reduction policies was subtracted from the industry and service sector energy consumption in DUKES to leave energy used by SMEs and some public sector organisations (figure 5, left hand side). 'Unconstrained' energy was taken to refer to SME consumption.

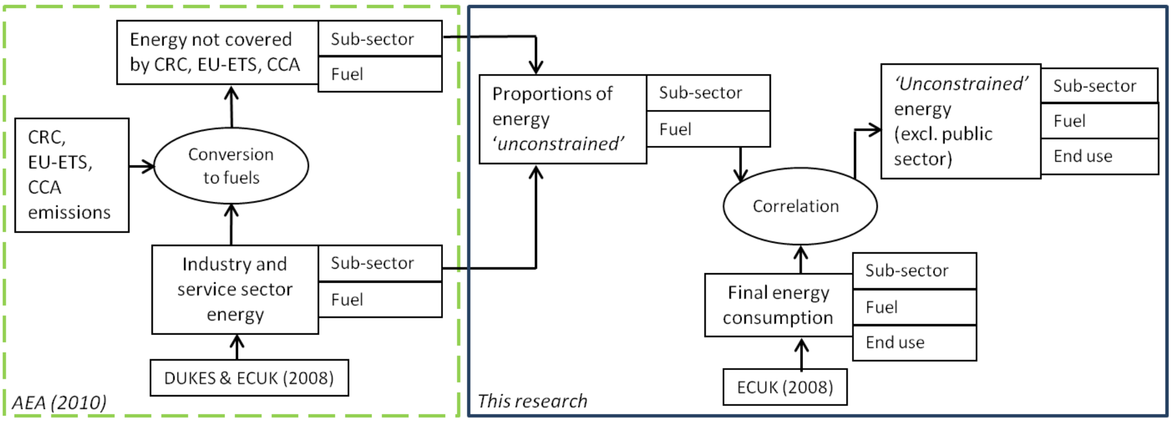


Figure 5 Calculation of '*unconstrained'* energy by sub-sector

In this study, the proportions of each fuel that were '*unconstrained'* in each activity group were determined from AEA's tables (total and unconstrained energy) (figure 5). These ratios were applied to the final energy consumption by sub-sector and by fuel, reported in ECUK. Education, health and government sub-sectors were removed leaving just businesses, in seven groups for the commercial sector and ten for industry, as listed in table 5. Some approximation was made in matching the industrial sub-sectors between ECUK and DUKES, since different versions of the Standard Industrial Classification (SIC) system are used.

Table 5 Business activity groups

Commercial Sector	**Industrial Sector**
Commercial offices	Metals (ferrous and non-ferrous)
Retail	Mineral products
Warehouses (excluding industrial)	Chemicals
Hotels and catering	Mechanical engineering
Transport and communication (building related energy use only)	Electrical engineering
Sport and leisure	Vehicles
Education *	Food, beverages
Health *	Textiles, leather
Government *	Paper, printing
Other (includes churches and community centres)	Other industries (manufacturing of wood products, furniture, rubber and plastics; recycling and water treatment)

* Public sector excluded in this analysis, to leave *unconstrained* businesses (mainly SMEs).
Source: (Pout et al. 2002; DTI 2002)

3.4.2 Results

Table 6 is an extract of service sector electricity consumption data published by DECC (DECC 2012). Categories relating to non-business buildings (the public sector and other buildings category) have been removed as these are not considered in the SME analysis. Four of the commercial sector categories, listed in table 5, were excluded because AEA were unable to disaggregate these categories (Forster et al. 2010). These are *sport and leisure*, *agriculture*, *miscellaneous commercial* and *construction*. In the 'end use' categories, *other* relates to lifts, pumps, laboratory, photographic and other specialised equipment (Pout et al. 2002). This gives a total of 64,700 GWh. Table 7 shows the calculated electricity attributed to '*unconstrained*' businesses (mainly SMEs). This is 25,257 GWh or 39% of the total in table 6.

Table 6 Service Sector Electricity (GWh) 2008

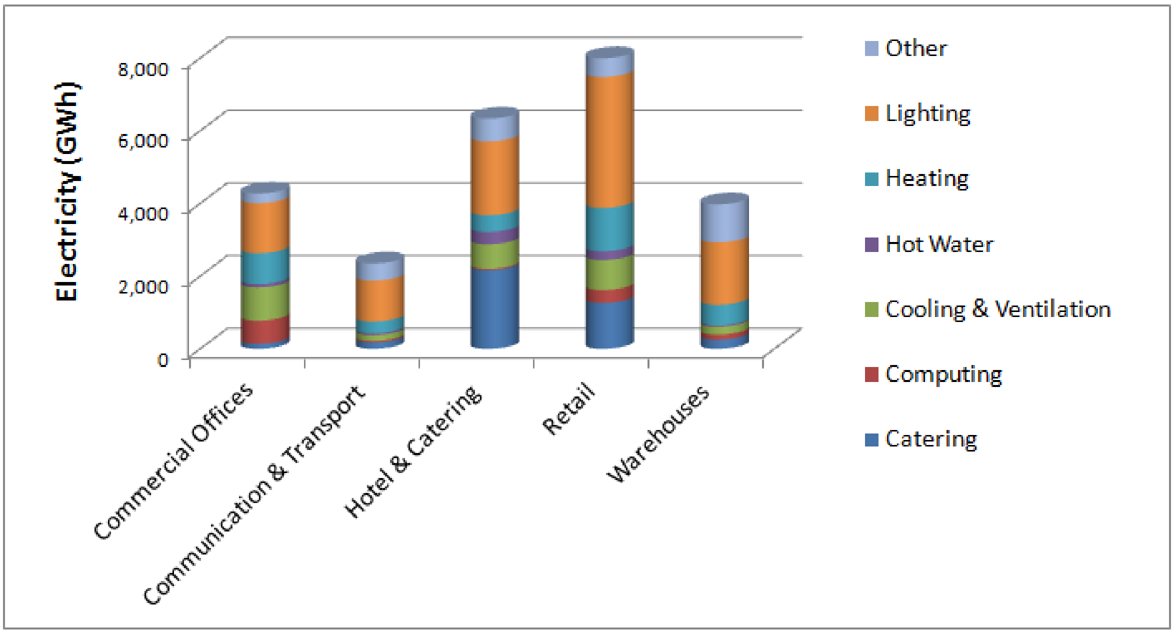
	Catering	**Computing**	**Cooling & Ventilation**	**Hot Water**	**Heating**	**Lighting**	**Other**
Commercial Offices	283	1275	1834	185	1689	2762	523
Communication & transport	355	90	319	99	647	2251	940
Hotel and catering	3610	62	1128	573	757	3388	1043
Retail	4577	1294	2986	878	4320	13057	2996
Warehouses	689	382	591	98	1529	4650	2837
Total, GWh	9515	3102	6859	1833	8942	26108	8341

Source: *DECC (2012)*

Table 7 'Unconstrained' service sector electricity (GWh) 2008

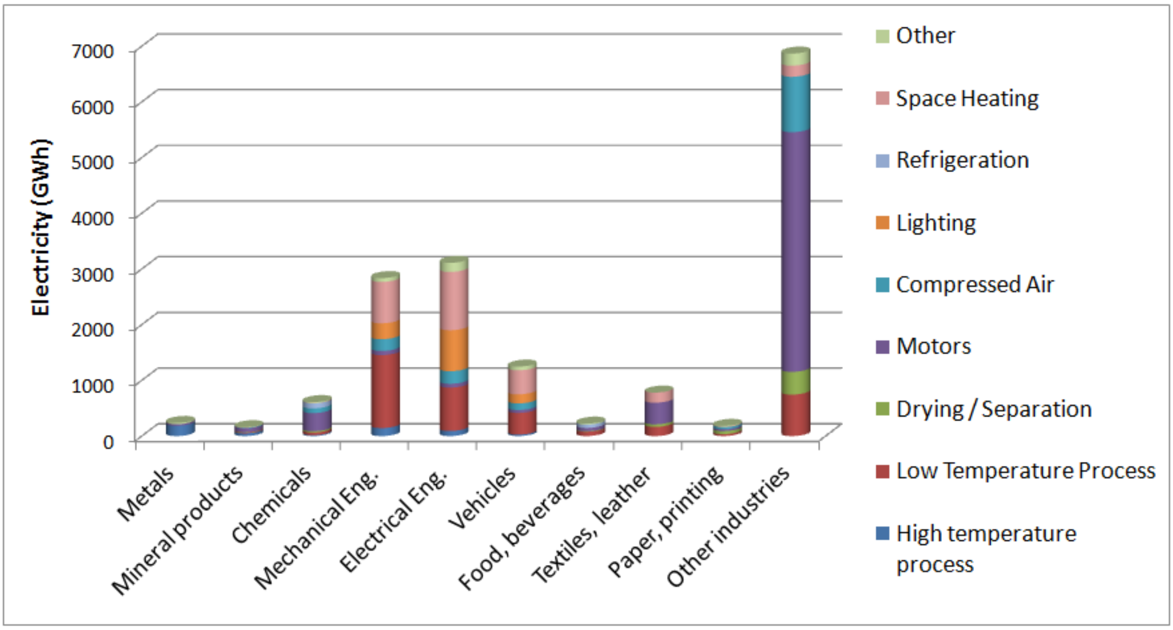
	Catering	Computing	Cooling & Ventilation	Hot Water	Heating	Lighting	Other
Commercial Offices	141	637	917	92	844	1381	262
Communication & transport	178	45	160	50	324	1126	470
Hotel and catering	2166	37	677	344	454	2033	626
Retail	1264	357	825	242	1193	3606	827
Warehouses	254	141	218	36	565	1717	1048
Total, GWh	4004	1218	2796	764	3380	9862	3233

Source: (DECC 2012; Forster et al. 2010)



Source: *DECC (2012)*

Figure 6 Commercial Sector: '*unconstrained*' electricity consumption by end use



Source: (DECC 2012; Forster et al. 2010)

Figure 7 Industrial electricity consumption: '*unconstrained*' consumption by end use

Figure 6 and figure 7 illustrate electricity consumption in the '*unconstrained*' commercial and industrial sectors respectively, broken down by end use.

3.4.3 Opportunities for Time-shifting of Electrical Loads

Active management of electricity demand will become more important as the proportion from non-dispatchable sources increases. Analysis of the end uses of electricity as well as business activities and locations is necessary to highlight where DSM may be possible, with smart grid technology. Smart grids may lead to carbon reduction through demand reduction or demand response or they will simply support carbon reduction.

The main form of demand response considered here is time-shifting of electrical loads away from peak periods. These are cutting back on consumption (for example, by dimming lighting) and generating electricity on site. Demand reduction arises from awareness raising which may be prompted by data from a smart grid. Electrical loads which are candidates for time-shifting are likely to be peripheral to the main business activity and are most likely to be heating, cooling and hot water.

In this thesis, *'the part of the building electrical load that could be reduced for short periods with minimal impact on the building occupants'* is referred to as '*discretionary load*'. It has been suggested that cooling may be turned down for up to 30 minutes, heating for up to 15 minutes and hot water for a period determined by the demand pattern and storage (Dolman et al. 2012). The temperature must remain within limits acceptable to the building occupants and adequate ventilation has to be maintained. If this is supplied mechanically, power will still be required by fans. Process loads may be suitable for time-shifting with sufficient notice or payment but this needs case by case evaluation.

Confidence in the data is good at the aggregate level but diminishes at lower levels. Electricity suppliers provide DECC with consumption data (DECC 2011a), from which business electricity use in DUKES is calculated. Allocation of energy to sub-sectors relies on data from the Government's Purchases Inquiry (PI) which asked around 6000 companies how much they spend on different types of fuel. These data are scaled in relation to the number of businesses in each SIC sector to match the totals in DUKES (DECC 2010). The most recent PI data are for 2006 since this survey has been suspended. The allocation of energy to specific end uses relies largely on surveys carried out in the 1990's (for the NDBS Project). Electrical cooling and IT are now more widespread which introduces some uncertainty in the end use allocations. The UK Green Building Council 2007 report that '*electricity use in non-domestic buildings has risen very closely in line with floor space'* [between 1992 and 2007]. More small electrical equipment (including computers) is now in use and this also increases the cooling loads. Display Energy Certificates (DECs) were introduced in 2008 for public buildings over 1000 m^2 in England and Wales (HM Government 2007). Each DEC is valid for one year and shows the annual electricity and fossil fuel consumption. This Regulation has been amended to include public buildings over 500 m^2 (DCLG 2012). DECs for buildings below 1000 m^2 are valid for 10 years. Analysis of the certificates from 31,800 buildings showed that the total energy consumed was close to the predicted benchmarks (Hong & Steadman 2013). However many building types had higher electricity consumption than expected and lower heating energy. This suggests that the carbon emissions had risen due to the greater CO_2 intensity of electricity than gas (the predominant fossil fuel).

Acceptable loads for time-shifting may be reduced for short periods without detriment to the business. Referring to figure 6 and figure 7, the largest blocks of discretionary demand emit the CO_2 stated in table 8 [1]. Collectively, this represents 6.8% of the estimated 49 Mt

[1] The CO_2 emission factor for electricity used is 0.541 $kgCO_2/kWh$, to maintain consistency with the previous work by AEA (Forster et al., 2010, p.72).

CO_2 emissions due to the *unconstrained* sector (Forster et al. 2010). The high demand for lighting (3606 GWh in retail) and motors (4303 GWh in other industry), figure 7 suggests opportunities for energy saving.

Table 8 Sectors with electrical loads considered most likely for time-shifting (‘*unconstrained’* sector)

	Commercial Sector ($ktCO_2$)	
Heating	Retail 645	Commercial Offices 457
Cooling	Commercial offices 496	Retail 446
Hot water	Hotel & catering 186	Retail 131
	Industrial Sector ($ktCO_2$)	
Heating	Electrical engineering 567	Mechanical engineering 402

Source: *AEA, 2010; ECUK, 2010*

DECC estimate that 20% of peak load in currently discretionary, consisting of hot water, heating, cooling, ventilation and some refrigeration (DECC 2014e). This is expected to increase at a modest rate to 24% by 2030 due to new electric vehicles and heat pumps.

Dolman et al. (2012) developed load profiles for the commercial sector disaggregated by end use, using data from half-hour meters and a limited quantity of sub-meter data. Considering 5pm on a winter weekday to be peak time, they estimated shiftable loads in each of three scenarios (‘*conservative*’, ‘*moderate*’ and ‘*stretch*’). The moderate scenario makes ‘*reasonably ambitious flexibility assumptions*’[2]. For the commercial sector only, the authors estimated the shiftable load as 1.2 GW (or 2.5 GW including lighting). It was assumed that the contribution that SMEs make to peak loads was in proportion to the contribution made by the ‘unconstrained’ sector to the annual electricity consumption. The proportion of ‘unconstrained’ service sector electricity calculated from tables 2 and 3 (36.3%) was applied to this estimate of shiftable load, for all thermal end uses excluding lighting, as 0.4 GW (36.3% of 1.2 GW).

[2] 50% flexibility for hot water, 20% for heating, cooling, lighting and refrigeration and zero for catering and IT (Dolman et al., 2012, p.31).

Time-shifting of electrical loads does not automatically reduce carbon emissions. (Hawkes 2010) noted that the CO_2 intensity of the generators that respond to a specific '*demand change'* determined the CO_2 increase or decrease. Marginal emissions factors (MEFs) were evaluated which represent the CO_2 intensity of a change in demand. Based on data from 2002 to 2008, Hawkes calculated that the MEF peaked (at 0.7 $kgCO_2/kWh$) when the system load reached around 35 GW_e. Further increases in load (equivalent to a winter peak of 55 GW_e) resulted in the MEF reducing to 0.55 $kgCO_2/kWh$. This is likely to be due to hydro (natural flow and pumped storage) supplying energy. The MEF fluctuates during the day (mainly within a band of 0.6 to 0.7 kg CO_2/kWh), even when demand is relatively stable. This is due to operational constraints on generators.

3.5 Application to DSM in Buildings

3.5.1 Building Thermal Mass

The building fabric stores heat such that the heating (or cooling) may be temporarily turned down although adequate ventilation must continue. The model must represent how the building fabric responds to transient heat gains from solar radiation, occupants, equipment and the HVAC system. The thermal capacitance of a building element may be defined as: '*the amount of energy required to raise the temperature by one degree'* (Spitler 2011) (equation 1):

$$C_{th} = MC_p = \rho V C_p \quad \text{Equation 1}$$

C_{th} is the thermal capacitance of the building element (J/K)
M is the mass of the building element (kg)
C_p is the specific heat capacity of the building element (J/kg.K)
P is the density of the building element (kg/m^3)

The effects of building capacitance on the heat gain are to delay the rise in temperature and to reduce the amplitude of the heat gain (Spitler 2011). The thermal mass absorbs heat and releases it gradually such that the peak temperature (on a hot day) is reached later and is lower. The location of the thermal capacitance in relation to the insulation is important in determining its effect on the internal temperature gain (Kossecka & Kosny 2002). The authors analysed the effect of the location of insulation and thermal mass in an external wall in order to determine annual heating and cooling loads for a house. The lowest annual heating and cooling energy was consumed in the cases where a concrete (high mass) layer was on the inside, immediately adjacent to the plaster. In the case of a cool climate (Washington DC) this configuration had the lowest cooling energy load and the second lowest heating load.

3.5.2 Building Regulations and Thermal Efficiency

The building envelope is important in regulating the heat loss from a building. The performance of '*thermal elements'*, such as walls and windows has been regulated by The Building Regulations since 1965 (Parliament 1965). The permitted U-values have reduced with subsequent updates. Consequently the age of the building is considered a proxy for thermal performance and heating energy consumption (Pout 2000). This is often assumed to hold for all building types. However, the oldest regulations relating to thermal performance apply if '*that building or part is intended to be used exclusively for the purposes of one or more dwellings'* (Parliament 1965), (Parliament 1972), (Parliament 1976). Despite this omission of non-dwellings, researchers such as Korolija et al. (2013) applied the Regulated U-values to office buildings and assumed that improvements in commercial buildings reflected those mandated for domestic ones. This approach has been adopted here. Table 9 summarises the maximum U-values permitted for elements of the building envelope under successive Regulations. From 1985 onwards this references the Part relating to '*buildings other than dwellings*'. In the 2002 Regulations, the maximum U-values for glazing are 2.0 W/m^2K with wood or PVC frames or 2.2 W/m^2K with metal frames. These data are applied in developing the building types in section 6.3.2.

Table 9 Maximum permitted U-values (W/m^2K) under The Building Regulations

	1965 / 1972	1976	1985	1990	1995	2002	2006 / 2010
External wall	1.7	1.0	0.6	0.45	0.45	0.35	0.35
Flat roof	1.42	0.6	0.6	0.45	0.45	0.25	0.35
Ground floor	1.42	1.0	0.6	0.45	0.45	0.25	0.25
Glazing	n/a	5.7	5.7	5.7	3.3	2.0 / 2.2	2.2

Source: *Parliament (1965), Parliament (1972), Parliament (1976), Parliament (1985), DEWO (1990), DEWO (1995), DTLR (2002), ODPM 2006), HM Government (2010).*

3.5.3 HVAC Systems in Relation to DSM

3.5.3.1 HVAC Systems in Office Buildings

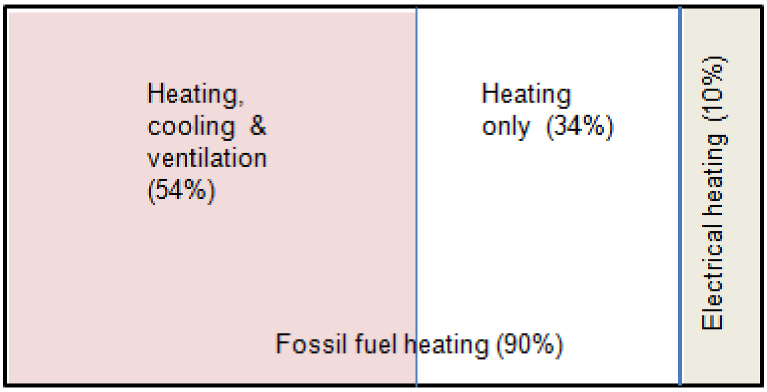
The distribution of HVAC systems in UK office buildings is needed in order to quantify the potential for DSM from heating and cooling loads. The quantity of UK office buildings with cooling or mechanical ventilation is unclear. This is complicated by the diversity of HVAC systems and no reported relationship to building age, floor area or business activity.

'*HVAC*' refers to '*the equipment, distribution systems and terminals that provide, either collectively or individually, the processes of heating, ventilating or air conditioning to a building or portion of a building'* (ASHRAE 2014). '*Air conditioning*' is '*the process of treating air to meet the requirements of a conditioned space.*' (ASHRAE 2014). This includes control of temperature and may include control of humidity. However humidity control was not included in the model developed in this research.

The proportion of office buildings with air-conditioning has grown significantly but precise quantities are not available. Hitchin & Pout (2000) report that 20% of commercial office space was air-conditioned in 1994 based on surveys carried out for BRE. The authors do not state how this was broken down by age or floor area of property. Caeiro et al. (2008) analysed the extent and type of air-conditioning in office buildings from street level surveys. The authors noted the type of air-conditioning equipment present in 260 buildings in three English cities (London, Leicester and Sheffield). The majority (58%) of buildings had floor areas less than 1000 m^2. Air-conditioning was present in over 50% of buildings over 500 m^2. Overall 62% of office buildings had air-conditioning visible from street level observations. Additional systems may have been present but were not visible. Hong & Steadman (2013) analysed the DECs of 22151 public buildings including 3334 classified as '*general office*'. The vast majority of these (c. 95%) were over 1000 m^2 since this was a requirement of DECs (HM Government 2007). The main heating fuel was stated as electricity for 423 (12.7%). Of the 2911 buildings heated by gas and other fuels, 48% had air conditioning or an installed ventilation system (mechanical or mixed mode). This suggests that the incidence of air-conditioning is increasing and is currently in 50-60% of office buildings.

For this research, it was assumed that at the present time, 90% of buildings have fossil fuel heating and 60% of these have cooling and mechanical ventilation, figure 8. The buildings with fossil fuel heating and cooling with mechanical ventilation (90% x 60% =) 54% were considered of interest for DSM.

Buildings with electric heating were excluded from the present day analysis in the building energy model (Chapter 6). These currently represent around 10% of the total stock. The division into heater types is not known but most electric heating was assumed to be on off-peak tariffs such as '*Economy 7*'. The effect of this tariff has been to shift a substantial portion of the space heating and hot water load from peak to off-peak peak periods, which demonstrates the effectiveness of demand side management. However it seems unlikely that further load could be shifted away from peak periods. Other electric heating consisting of on-peak plug-in electric heaters make up an unknown proportion of overall heating. Remote, automatic controls would be required in order for a significant portion of this load to be turned down in response to a request from an electricity company (section 3.5.3.2). These heaters were excluded from this study.



Source: *Caeiro et al. (2008), Hong & Steadman (2013)*

Figure 8 Proportion of HVAC systems in offices used in this research

There is no reported relationship between HVAC type and built form type or building age. Deep plan buildings are more likely to require mechanical ventilation (Steadman, Bruhns, Holtier, et al. 2000). However these buildings are not separately identified in the literature on HVAC types. The UK Government's 'Market Transformation Programme' (MTP) publishes data on quantities of HVAC systems believed to be installed in the building stock (Defra 2010). The MTP data were derived from sales records collected by BSRIA and does not state the proportion that were installed in new buildings compared with refurbished property or how many were installed in office buildings, compared with any other category. The authors rank their confidence in some of their sources as '*low*', especially in relation to quantities of fan coil units and future projections.

Many different HVAC system types exist and it is not possible to identify a characteristic system type for any building type. A partial picture is obtained from surveys of properties reported in the literature, some of which are summarised below.

'The Non-domestic building energy fact file' presents data on the occurrence of building services in non-domestic buildings (Pout et al. 1998). This report contains data for England and Wales on the floor area of office premises with and without 'central heating' and 'air conditioning' systems obtained from VOA records. These data are disaggregated by building age band, floor area size band and bulk class ('*office*', '*retail*', '*factory*' and '*warehouse*'). '*Central heating*' and '*air conditioning*' are not defined. The report also presents detailed results from a survey of 250 buildings in the service and light industrial sectors from 1993-1994. These data are not correlated with business activity or floor area and the HVAC types are left undefined.

In the NDBS Project, Rickaby & Gorgolewski (2000) developed a classification system for HVAC systems in buildings. They classified HVAC systems into principal types related to size ('*small scale*', '*intermediate scale*', '*packaged A/C*' and '*large scale HVAC*'). These were broken down into sub-types with a focus on secondary systems (heat distribution). Data are presented on the distribution of the HVAC systems in the 419 premises surveyed. This includes the quantities of system types in different building types. However the value of this is severely limited due to the small numbers of premises and of HVAC types. For example, only 78 premises were classified as '*commercial office*', making it impossible to evaluate statistically significant findings. An unknown number of buildings had more than one HVAC system.

The energy consumption of HVAC systems in office buildings is discussed in '*Energy Consumption Guide-19: Energy Use in Offices*' (Action Energy 2000). A '*large number of occupied buildings*' were surveyed during the 1990s but the quantities are not stated. Energy benchmarks were developed. Buildings were categorised into four types: *'naturally ventilated cellular'*, '*naturally ventilated open plan*', '*air-conditioned standard*' and '*air-conditioned prestige*'. The allocation of these categories to buildings is not precise and is largely related to floor area. This *Guide* mentions a small selection of HVAC systems: air cooled chillers, VAV systems and gas and oil boilers. No relationship between HVAC types and building categories is stated. Updated energy benchmarks are given by CIBSE in '*Energy Benchmarks TM46:2008*' (Field et al. 2008). This gives electricity and fossil fuel consumption standards for all office buildings but does not distinguish HVAC types or buildings that are naturally ventilated. A review of these benchmarks based on Display Energy Certificates (DECs) for public buildings lists the HVAC system categories used in DECs (Hong & Steadman 2013). These are high level categories and some are ambiguous (such as '*mixed-mode with mechanical ventilation'*). The report does not state where a building has more than one system type.

The above sources provide valuable data from real buildings on HVAC systems in offices. However they do not give a clear picture of the relationship between HVAC system types, building ages, floor areas or built form types in UK office buildings.

CIBSE identified 20 types of air-conditioning system which could be combined with several different heating system types (CIBSE 2012). Shahrestani et al. (2013), in a study of the energy performance of HVAC, systems chose to represent 36 centralised HVAC systems in their simulations. These consisted of three primary systems combined with 12 secondary systems. The primary systems convert the fuel (such as gas or electricity) into heat and the secondary systems distribute the heat to the occupied parts of the building (Shahrestani 2013). The primary systems were: (a) gas boiler with reciprocating air cooled chiller, (b) gas boiler with absorption chiller and cooling tower and (c) combined heat and power (CHP) with absorption chiller and cooling tower (CCHP) (Shahrestani et al. 2013). The secondary systems were constant air volume (CAV) and variable air volume (VAV) distribution systems with options of heat recovery, economiser and terminal reheat units, making 12 combinations. In this research the following primary and secondary systems were also considered: air source heat pump (ASHP) and dedicated outdoor air system (DOAS). The features of these systems that support or inhibit DSM are evaluated in section 3.5.3.2.

A heat pump is a *'thermodynamic heating / refrigerating system to transfer heat. The condenser and evaporator may change roles to transfer heat in either direction. By receiving the flow of air or other fluid, a heat pump is used to cool or heat'* (ASHRAE 2014). The heat source may be the outdoor air, the ground or a water source. DOAS is '*a* *ventilation system that delivers 100% outdoor air to each individual space in a building*' (ASHRAE 2014). DOAS is commonly supplied with a constant air volume (CAV) fan (Shahrestani 2013). In this research, a variable air volume (VAV) fan was selected since this would allow the air flow to be adjusted during periods of low occupancy (Ingersoll-Rand 2013), (Int-Hout & Wilbar 2014).

The primary systems generate heat. A boiler is '*a closed, pressure vessel that uses fuel or electricity for heating water or other fluids to supply steam or hot water for heating, humidification, or other applications'* (ASHRAE 2014). In this context, natural gas is used to heat water for space heating. A 'chiller' is a *'refrigerating machine used to transfer heat between fluids'* (ASHRAE 2014). This has a compressor, condenser and evaporator but cannot be reversed to deliver heat to the occupied space, like a heat pump. An absorption chiller is a '*refrigerating machine using heat energy and absorption input to generate chilled water or other chilled liquids'* (ASHRAE 2014). Combined heat and power (CHP) systems '*generate electricity and useful thermal energy in a single, integrated system'* (ACEEE 2009). The generation of electricity using thermal power plants produces heat which is normally released into the environment. A CHP system recovers some of this heat for useful purposes such as space heating or to drive an absorption chiller to provide cooling.

The secondary systems distribute warm or cool air to each part of the building. Constant Air Volume (CAV) systems maintain a constant airflow but vary the temperature to meet heating and cooling loads (CIBSE 2005). With Variable Air Volume (VAV) systems, the volume of air is changed to meet the heating or cooling requirement (CIBSE 2005). Heating and cooling coils modify the supply air temperature and the fan speed is adjusted. VAV systems are more efficient than CAV because the fan power is reduced during part-load conditions (Shahrestani 2013).

3.5.3.2 Factors that affect the suitability of an HVAC System for DSM

The key requirement for an HVAC system to provide demand side management (DSM) is an electrical load that can be turned down. Motegi et al. (2007), state three factors that make HVAC systems suitable for DSM: (a) they consume '*a substantial portion of the electric load in commercial buildings*', (b) the thermal storage of the building allows them to be turned down for short periods '*without immediate impact on the building occupants*' and (c) it is common for HVAC systems '*to be at least partially automated*' with management and control systems. This makes it possible to reduce electricity consumption rapidly in response to a signal from an electricity company. The control system may enable the turn down for an entire building or individual zones. The load to be turned down consists of cooling and heating, where the heat source is electricity.

Table 10 Key features of centralised HVAC systems identified from the open literature in relation to DSM

System	Electric loads	Potential to reduce electricity demand?
Heating:		
Gas boiler	Controls	No
Combined heat and power system	Controls	Yes: CHP increase electricity generation
Air source heat pump	Compressor and condenser fan	Yes: decrease heating or cooling
	Circulation pump	Yes if variable speed
Cooling:		
Reciprocating air cooled chiller	Compressor and condenser fan or cooling tower	Yes: decrease cooling demand
Absorption chiller and cooling tower	Chiller	Yes: decrease cooling demand
Distribution systems:		
Constant air volume	Air circulation fan	No
Variable air volume	Air circulation fan	Yes
Dedicated outdoor air system	Air circulation fan	Fan: yes if variable flow

Source: *(Motegi et al. 2007; Shahrestani et al. 2013; CIBSE 2005)*

The characteristics of centralised HVAC systems that relate to DSM are summarised in table 10. The electrical load of a gas boiler is limited to the control system which consumes very little power. During routine operation, the electrical output of a CHP plant will be adjusted to meet demand within the building. Beyond this, the output may be increased to supply to the local electricity grid and contribute to DSM locally. In non-domestic buildings, heat pumps often supply both heating and cooling. Reducing the demand for these services (by temporarily altering the setpoint) will reduce the electrical demand of the heat pump. Each of the above systems has a circulation pump. If the pump is variable speed, the building electrical demand will be reduced by a small amount if the heating or cooling is turned down. With either type of chiller, if the cooling demand is reduced, the electrical input will be reduced. In a building with more than one chiller, one may be shut-down temporarily during a DSM event while the others operate un-interrupted (Stannard & Hewitt 2014). Each of the distribution systems in table 10 consumes electricity to power an air circulation fan. If this is variable speed, then the fan power may be reduced during a DSM event, subject to ventilation requirements (Stannard & Hewitt 2014). Each of these systems is controlled centrally. In this research, two primary systems were chosen: gas boiler and air source heat pump (ASHP). Gas heating is popular in UK with most properties in the Reading area connected to the gas grid (Khan & Stadnyk 2013). ASHPs can be installed in existing buildings. A significant increase in heat pumps in all buildings would support a lower carbon future as the carbon intensity of electricity is reduced (National Grid 2015a).

3.5.3.3 Examples of HVAC systems providing load reduction in DSM schemes

DSM has been deployed by utility companies in USA to reduce peak demand since mid-1980s (Gellings 1996). For example, in 2003-2004 the electricity suppliers in California carried out a pilot of charging residential customers higher prices at peak times (2pm to 7pm) (Herter 2007). Large consumers made the greatest reductions (in kW) while small consumer saved the largest proportion of their expenditure. In Great Britain, some large electricity consumers participate in DSM through a portfolio of ‘balancing services’ procured by National Grid (National Grid n.d.). These cover the spectrum from ‘*frequency response*’ services where load reduction may be required within 2 seconds to ‘*reserve*’ services where a response time of up to 4 hours is permissible. One service in the second category is Short Term Operating Reserve (STOR), which was compared with the model output in this thesis. STOR is described in section 4.4.1.

The University of East Anglia now reduces the electricity demand of air conditioning to support National Grid’s system balancing (Open Energi 2015a). Following an agreement in 2013 with Open Energi, air handling units and chillers with a combined consumption of 1 MW are now equipped with automatic demand reduction equipment. This increases or decreases the demand on a ‘*second-by-second-basis*’ in response to changes in the frequency of the electricity supply, which signals imbalances in supply and demand. The electricity consumption of this equipment is only adjusted for a few minutes at a time so that students and staff remain comfortable. The University expects to earn more than £50,000 over three years through providing this service (UEA 2014).

SMEs have participated in recent trials of DSM, led by some of the distribution network operators (DNOs). In the New Thames Valley Vision (NTVV) trial, air conditioning systems and lifts were turned down (Stannard & Hewitt 2014). 83 DSM ‘events’ took place involving 11 companies. Customer equipment was automatically turned down for periods of 30 minutes to 2 hours. For the DSM events of one hour duration, the range of load reduction was 0 kW to 51 kW, with a mean of 21 kW. SSEPD were concerned that for some customers the magnitude of load reduction was uncertain since the demand either side of the load shift event was ‘*volatile*’.

3.5.4 Quantifying the Office Floor space in Reading Borough

Section 3.4 identified ‘commercial offices’ as an important activity category for DSM. This is assumed to map to office buildings. ECUK data for commercial offices are compiled by BRE by disaggregating energy totals in DUKES using their non-domestic building energy model (Pout et al. 2002), (Goodright 2015). The end use data relies on energy audits carried out by Sheffield Hallam University during 1990’s for the NDBS Project.

Table 11 Business floor space by main category in Reading and South East England

Floor area, 2012 (thousands m^2)	**Reading**	**South East**
Offices	565	14411
Retail	533	16913
Industrial	632	35627
Other	89	6545

Source: *VOA (2012)*

In Reading Borough, office floor area accounted for 31% of rateable space in 2012, (table 11) VOA (2012). According to the VOA, the ‘industrial’ category breaks down into warehouses and factories, with the result that ‘offices’ are almost certainly the largest type in Reading by floor area (VOA 2012b). The category, 'other' consists of halls, sports and leisure space.

One objective of this work was to quantify DSM opportunity within Reading Borough. To achieve this required the floor area of office buildings, disaggregated by age band, so that differences in building insulation could be accounted for.

Office floor space for each local authority in England and Wales, broken down by age band is available for 2004, from ODPM (2005). Unfortunately the breakdown by age band has not been updated; only total areas have been published for each local authority. This is based on data which VOA holds. VOA publish floor area by local authority for offices for successive years; the most recent being for 2012 (VOA 2012a). The VOA record net internal area (NIA) for offices (VOA 2016). NIA '*includes most space useful to the business of an occupant, and excludes common areas, stairwells, and foyers. The lift shafts, walls and columns of a property are also excluded*' (VOA 2012b). The total floor areas for 'offices' published by the VOA exclude non-taxable space such as atria and stairwells in shared buildings.

Commercial property in Reading Borough was recorded by an RBC officer in 2004 (Worringham 2004). The survey records offices and light industrial units, mainly in industrial areas. This accounts for 52% of the office floor space in table 12. The business use (office, industrial or retail), post code and estimated age are listed for each property. The gross external area (GEA) was estimated using building outline polygons on MapInfo™.

Table 12 Age distribution of office floor space, NIA, for Reading and the South East, 2004. Asterisks '*' indicate data that could disclose the identities of the organisations. For Reading, the non-*disclosed* floor area was counted in the '2001-03' age band.

	Not known	Pre 1940	1940-70	1971-80	1981-90	1991-2000	2001-03	All ages
Reading *(thousands m^2)*	*	73	74	68	253	128	*	661
	0	11.1%	11.2%	10.3%	38.2%	19.4%	9.8%	
South East *(thousands m^2)*	837	2 960	2 360	1 786	4 429	2 577	1 114	16 063
	5.2%	18.4%	14.7%	11.1%	27.6%	16.0%	6.9%	

Source: *ODPM 2005*

Table 12 gives the floor area for offices in Reading, broken down by age band from ODPM (2005), compared with the south east region. Asterisks '*' indicate low values that are considered '*disclosive'*.

'*Data is potentially disclosive if, despite the removal of obvious identifiers, characteristics of this dataset in isolation or in conjunction with other datasets might lead to identification of the individual, business or other entity to whom a record belongs. Information (for example about sales by business) can also be potentially disclosive if it gets too close to revealing the contribution of an individual business to the public, or to a competitor*.' (data.gov.uk 2014).

In practice, data is considered '*disclosive*' if five or fewer entities (such as, electricity meters, properties or businesses) are grouped together (DECC 2014h). The difference (of 65 000 m^2) between the known values for Reading (pre-1940 to 2003) and the total was allocated to the 2001-03 category in the calculations below.

VOA (2012) gives total floor space for Reading Borough for each year but without an age band breakdown. In 2012, the area was 565 000 m^2. In order to disaggregate this by age band, the lifespan of existing buildings was estimated and the area of buildings constructed since 2000 was updated.

Worringham (2004) calculated the GEA of the offices constructed between 2001 and 2003, as 114 000 m^2. This is equivalent to 88 000m^2 NIA, using the conversion factor of 1/1.3 proposed by Bruhns et al. (2000). A large development from 2001 to 2010 that could be verified was added, resulting in 9050m^2 additional NIA (Knight Frank et al. 2014).

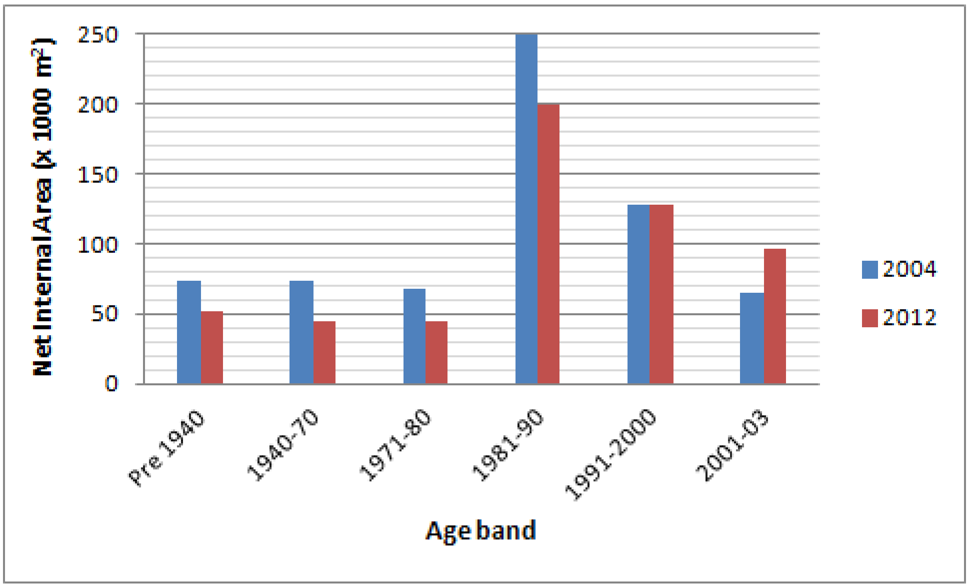
The age of buildings at demolition was required in order to account for the reduction in total floor area from 2004 to 2012. O'Connor (2004) analysed the records relating to 105 commercial and 122 residential buildings in Minneapolis / St Paul that were demolished between 2000 and 2003. The age of the commercial buildings at demolition is given within a band of 25 years (0 to 25, 26 to 50 and so on). 57% of these buildings were no more than 50 years old and most had concrete or steel as the structural material. Wood framed buildings generally lasted longer but are less common in UK. Office buildings known to the author that have been or will shortly be demolished in Reading are listed in table 13, based on observations and conversations with colleagues at RBC. These are concrete structures, which is consistent with peak demolition after 26 to 50 years of use.

Table 13 Demolition of office buildings in Reading

Building	**Lifetime**	**NIA (m^2)**
Energis House	1972 to 2014 (42 years)	9 290
Civic Centre	1977 to 2015 (planned) (38 years)	17 350
Western Tower and Station Hill offices	c.1965 to 2015 (50 years)	20 100 [a] 25 000 [a]
Aldwych House	c.1980 to 2014 (24 years)	Unknown
Nugent House	1973 to 2013 (40 years)	Unknown

Source: *Personal communication with RBC colleagues, Display Energy Certificate, J Mould (2014)*

[a] *Floor areas of planned office buildings with approximately the same footprint and height as those being demolished* (Savills & Strutt & Parker 2014).



Source: *ODPM (2005),* VOA (2012) *& author's analysis*

Figure 9 Breakdown of office floor area by age band for Reading Borough

The breakdown for 2012 in figure 9 was developed from the above analysis. The aim was to keep the same overall profile of ages. The age bands for buildings constructed before 1980 were reduced by 35%; those from 1980s by 21%. More recent floor space was not reduced. In the analysis of building electricity (section 6.3.2), buildings from 1980 and earlier were grouped together, based on thermal performance in The Building Regulations (shown in table 14).

Table 14 Estimated breakdown of commercial offices in Reading by age, 2012

	Up to 1980	1981-90	1991-2000	2001-10	All ages
NIA (x 1000 m^2)	140	200	128	97	565
Proportion	*24.8%*	*35.4%*	*22.7%*	*17.1%*	

Source: *VOA (2012)* ('*All ages*' column), author's analysis

3.5.5 Variation in Energy use due to Occupancy

Clevenger et al. (2014) simulated energy use in commercial buildings and calculated that human behaviour affected annual energy consumption by 150% and peak load variation by 140%. Infiltration and ventilation rates had the largest impact on energy demand. (Salat 2009) proposed a factor of 2 to 2.6 for the influence of occupants' behaviour.

3.6 Conclusion

Smart grids are expected to bring new incentives for SMEs to contribute to carbon reduction, through incentives for demand side management. A lack of clarity and definition in energy use data presents a barrier to immediate, on-site carbon reduction initiatives. SMEs, the buildings they occupy and the end uses of energy are diverse and not well documented. The challenges of electricity grid de-carbonisation introduce a different opportunity, whereby consumers could receive incentives to support off-site initiatives through responsive energy management.

Existing energy models of businesses and non-domestic property are valuable but they require updating to identify opportunities for SME carbon reduction. Energy consumption data collected in the 1990's are useful but the division into end uses is less reliable since electricity consumption has increased due to IT equipment and cooling.

This initial analysis has identified discretionary electrical loads in the commercial and industrial sectors, a proportion of which should be suitable for load-shifting. These are space heating, cooling and hot water in the commercial sector and heating in industry. The large electricity use by motors in industry and lighting in the commercial sector suggests scope for energy saving. SMEs reducing their electrical loads at peak times may have a minor impact on carbon emissions. There is not a straight forward correlation between time of day and carbon intensity of electricity due to operational constraints on generators.

Modelling of business premises and energy consuming equipment is necessary in order to predict the scope for load-shifting. The equipment type and the profile of its use will affect the potential saving. Factors that affect heat generation and loss need to be modelled for complete buildings to understand the acceptability of load-shifting. Electrical loads need to be aggregated across a group of buildings in order to have enough load for DSM.

4. GB Electricity Network

4.1 Introduction

SMEs make up the vast majority of companies and the incentives for energy management are small. Chapter 2 suggested that smart grids could support carbon reduction through DSM but that the rewards from carbon reduction for many individual SMEs would be trivial. Chapter 3 analysed previous classifications of buildings and businesses and noted the heterogeneity of the stock is a significant barrier to action. The analysis indicated that electrical heating and cooling in offices is a likely source of shiftable load.

The objective of this chapter is to understand what DSM services SMEs can offer to electricity companies. This chapter presents essential background information on the structure of the electricity industry. The roles of the different companies are outlined and the challenges they face as energy consumption patterns change. DSM services that may be relevant to groups of SMEs are described. These are used to inform the development of multiple building scenarios in chapter 6.

4.2 The GB Electricity Industry

Most electricity in Great Britain is generated by large power stations and connected to the electricity transmission network (Energy UK 2015). This network consists of high voltage cables which connect generators and European interconnectors with the GB distribution network (National Grid n.d.). The distribution network carries electricity at lower voltages to customers. Electricity suppliers are responsible for retail connections and meter reading.

National Grid has a dual role as owner of the transmission network in England and Wales and System Operator for the GB transmission network. As System Operator, National Grid is mandated to maintain system balance at least cost and promote innovative solutions (National Grid n.d.). Any imbalance in supply and demand is measured by a deviation in system frequency away from 50 Hz. The System Operator is required to maintain the system frequency at 50 Hz ±1% (Parliament 2002). Low voltage supplies must be at 230V +10%,-6%. There must also be negligible harmonics, voltage spikes, fluctuations or power outages (BSI 2010).

Each distribution Network Operator (DNO) is licensed by Ofgem to distribute electricity within a geographical area (Ofgem 2016b). In Great Britain 14 DNOs own, operate and maintain the electricity distribution network within their license areas. These DNOs are owned by six companies. In addition, seven independent DNOs (IDNOs) develop, operate and maintain smaller distribution networks within the DNO areas (Ofgem 2015b). Generally these networks extend DNO networks into new housing or commercial developments. The distribution network is almost unmanaged and DNOs have little knowledge of the volume or destination of electricity.

Electricity cannot be stored to any appreciable extent so supply and demand have to be matched in real time. National Grid, as GB System Operator is responsible for matching supply and demand. Although electricity is generated and consumed continuously, it is traded on the wholesale market in half-hour blocks or settlement periods (SP) (Elexon 2013b). Energy Suppliers have to determine in advance how much electricity they will require for each SP and generators have to calculate how much they can offer for each SP. Contracts have to be agreed at least one hour before the SP in question, known as 'gate closure'. After this point, the contracted volumes of electricity must be generated and supplied. However the electricity supplied and generated may not be exactly the same because of errors in forecasting demand, faults with generators or electricity network power outages. The System Operator is then responsible for system balancing. If too little electricity had been contracted from generators, this would mean accepting offers of additional generation or demand reduction.

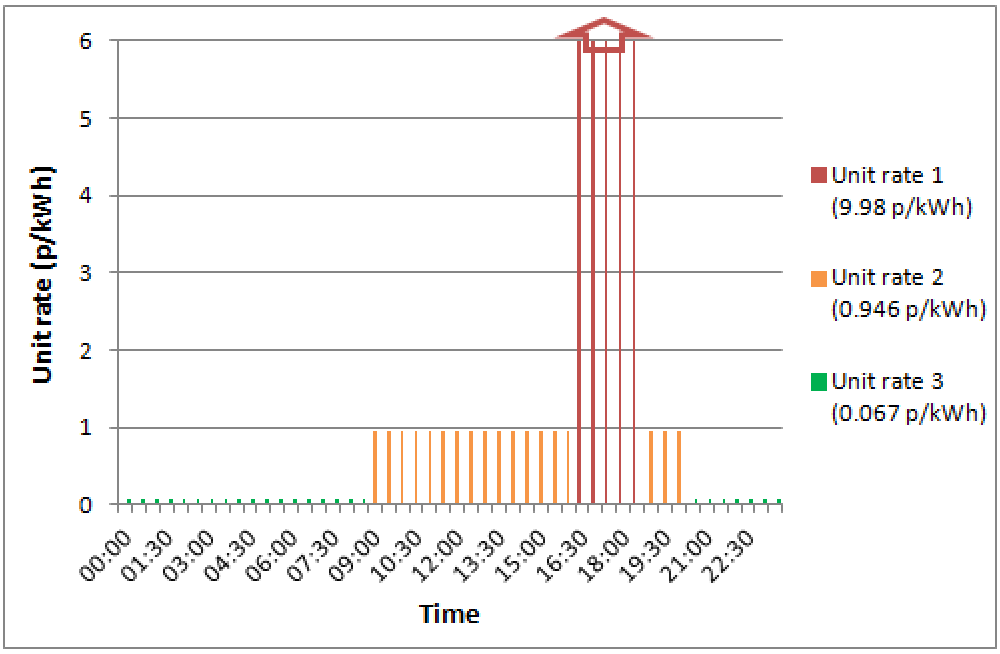
The imbalance of electricity from each SP is calculated and payments are made (Elexon 2013b). The vast majority of customers have non half-hour meters, which are read infrequently. However the volume of electricity consumed by these customers for each SP is needed to complete the settlement process. Elexon estimates this usage by classifying customers into 8 'profile classes' and calculating 'regression coefficients' for each SP (Elexon 2013a). Every meter is allocated a profile class: 1 and 2 are domestic; 3 and 4 are small non-domestic consumers and 5 to 8 are larger non-domestic consumers. Class 4 is 'Economy 7'; class 3 is for *'non-domestic unrestricted'* customers (Elexon 2013a). Half-hour meters are installed in a random selection of customer sites in each class and the electricity is recorded. Within each profile class, a set of 48 regression coefficients is calculated for each season and day type. The Elexon seasons are spring, summer, high summer, autumn and winter and the day types are weekdays, Saturdays and Sundays (Elexon 2013a). The regression coefficients determine the relationship between the demand and the temperature, the day length and the day type. In this thesis, regression coefficients will be used to calculate the profile of consumption during a day, based on the total consumption for that day (section 6.3.9). Elexon seasons do not match National Grid’s seasons for Short Term Operating Reserve (STOR): the Elexon winter season is the entire period on GMT (Elexon 2014). This is longer than National Grid’s STOR season 5 (described in section 4.4.1).

4.2.1 Charging for Electricity Supply

The wholesale price of electricity fluctuates during the day, reflecting the balance of supply and demand (Nord Pool Spot 2016). Currently most SMEs pay a constant price per unit during the day but this is expected to change. In GB, the peak price is typically around 1700 to 19:00 GMT during winter weekdays. Large consumers with half-hour meters already pay a higher unit charge (p/kWh) at these times, which reflects the stronger demand.

The tariffs for smaller non-domestic electricity consumers are expected to reflect the wholesale price when new meters are installed. Smart meters will be installed in the premises of the smallest non-domestic consumers with profile classes 3 and 4, including most SMEs by 2020 (section 2.6). It is likely that new tariffs reflecting the cost of supply will be offered (DECC 2013b). A separate programme, which was completed in 2014, installed ‘advanced meters’ in the premises of customers with profile classes 5 to 8 (Ofgem 2014). An advanced meter measures the electricity consumption every half-hour and provides the supplier with remote access to the data but has less functionality than a smart meter. From November 2015, when a customer with an advanced meter renews their contract or changes supplier, the energy supplier will use the customer’s half-hourly consumption data to calculate the supply costs (Ofgem 2015a). This will become mandatory by April 2017. New rules encourage suppliers to offer time of use tariffs that reflect the wholesale price of electricity.

National Grid charges users of the transmission network (generators and consumers) for the cost of installing and maintaining it (National Grid n.d.). Consumers with half-hour meters pay Transmission Network Use of System (TNUoS) charges. This cost is strongly affected by the three periods of highest winter demand, known as 'Triads' (Boyle 2015). Triads occur between 1st November and end of February, separated by at least ten days. National Grid uses the Triads to determine the demand charges for customers with half-hour metering (National Grid, 2015). The timing of the Triads is determined retrospectively after the end of February. The charge due to the Triads effectively drives half-hourly metered customers to reduce consumption during these periods, so making demand flatter (Boyle 2015). During the period: 1990/1 to 2013/14, 85% of triads occurred during the 17:00 to 17:30 period (National Grid 2016), (National Grid 2014d). 10% occurred during the 16:30 to 17:00 period and 5% from 17:30 to 18:00. Almost all have been on weekdays.



Source: *SSEPD (2014)*

Figure 10 Unit rates charged by SSEPD to half-hourly metered customers on weekdays, connected to their low voltage network

DNOs charge energy suppliers and large consumers for the use of their distribution network. These charges are divided into bands according to the time of day, to reflect demand. These costs are itemised for large consumers with half-hour meters; for smaller consumers these costs are hidden. Known as 'Distribution Use of System' (DUoS) charges, they depend on the supply voltage and type of metering. These usage charges include a significant time of day element in addition to fixed charges for supply (SSEPD 2014). DNOs divide the day into 'red', 'amber' and 'green' time bands, with 'red' being the period with the highest charges and 'green' with the lowest. The schedule of these periods varies between DNOs but in all areas except the north west 'red' bands cover the period, 17:00 to 19:00 (Swandells 2014). Scottish and Southern Energy Power Distribution is the DNO serving Reading (SSEPD 2012a). SSEPD's red band applies from 16:30 to 19:00 on weekdays, including bank holidays throughout the year. The amber time band applies from 09:00 to 16:30 and 19:00 to 20:30 on weekdays. The green band applies at all other times, including all weekend. A half-hour metered customer connected to SSEPD's low voltage network (below 1 kV) would pay the unit charges in figure 10. This highlights the cost of consuming electricity through a half-hour meter in Reading between 16:30 and 19:00 on weekdays compared with other periods.

4.3 Electricity Network Challenges

The UK faces simultaneous challenges to reduce the carbon intensity of energy supplied, to minimise prices to consumers and to maintain security of supply (section 1.1). The cumulative effect of power station closures, increasing wind generated electricity and more electricity for heating and transport require substantial investment. With the involvement of electricity consumers it is expected that this effect will be mitigated (section 2.6). The development of smart grids provides a means for electricity network operators to manage the demand of all customers which has not previously been possible. Smart grids enable two-way communication between supplier and consumer and provide the means for time of use tariffs or direct control of customer loads.

This management of customer load is referred to as demand side management (DSM). There is no single definition of this term 'DSM' which was first used by Clark Gellings of the Electric Power Research Institute in 1980's:

'DSM is the planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape' (Gellings 1985).

This definition is from a utility company and places the emphasis on what that company will do to persuade its customers to alter their usage. A more recent definition of DSM is: '*supporting customers to undertake short term shifting or flexing of load by changing demand patterns, increasing export or taking excess energy from a network'* (DECC 2014b). This definition lists a number of alternative actions and was adopted in this thesis.

For an electricity customer, DSM may consist of reducing consumption or exporting electricity to the grid, from a local generator. This thesis only considers demand reduction. However a large proportion of current DSM consists of local generation (National Grid 2015b).

Gellings (1985) states six ways in which DSM may alter the demand profile. Of these, 'load-shifting' is considered in this research. This '*involves shifting load from on-peak to off-peak periods*' (Gellings 1985). This makes use of a storage system to enable the load to be shifted. This could be a hot water cylinder or the fabric of a building. This assumes that the load can be re-scheduled and that there will be a period when energy demand increases, compared with business as usual (BaU). However '*the amount of energy recovered may exceed the amount of energy curtailed because of losses in the storage or energy conservation process*' (Strbac 2008).

4.3.1 Current DSM Services

The System Operator has a mature suite of services to enable supply and demand to be balanced (Elexon 2013b). These could be classified in terms of the response time required by the provider, which spans a range from one second to 4 hours (National Grid n.d.). One service considered applicable to aggregated SME loads is Short Term Operating Reserve (STOR), described in section 4.4.1. This is based on the magnitude and duration of the load shift as well as the sustain time and the minimum 'recovery' period before a subsequent DSM request. Some organisations already provide a STOR service via an aggregator (National Grid 2015c). Ofgem define aggregators as '*third party intermediaries specialising in coordinating or aggregating demand response from individual consumers to better meet industry parties' technical requirements for specific routes to market*' (Hay & Macwhinnie 2015). An aggregator may combine the load reduction from many companies in order to meet the minimum requirements for a service such as STOR.

DNOs do not offer any commercial DSM services although they have been evaluating their potential concurrently with this research. Ofgem has provided £500 million towards the cost of DSM trials as part of its Low Carbon Networks Fund (LCNF) (Ofgem 2016a). The aim is to help DNOs to develop approaches to deliver lower carbon electricity at affordable prices for their consumers while maintaining security of supply. DNOs are interested in DSM in order to avoid or defer capital expenditure and the related disruption to customers

(Ward et al. 2012). If the capacity of the network assets at a specific location is satisfactory, except during brief surges in demand, then a DNO may prefer to reduce peak demand if possible rather than invest in new infrastructure. DSM at specific times and locations may also help support fault management. For example, this could allow a larger group of customers to continue receiving some electricity from a single feeder, if the second had to be repaired. DNOs are interested in the potential for DSM to help manage local renewable generation and future additional loads from vehicles and heat pumps (Ward et al. 2012).

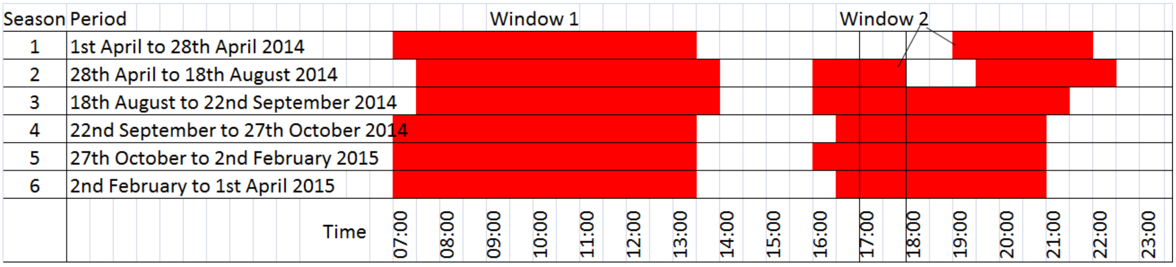
Energy Suppliers do not currently offer any commercial DSM services but may consider these in future (Ward et al. 2012). DSM could benefit energy suppliers by reducing demand for electricity when the wholesale price is high or when it fluctuates due to a high volume of wind generated electricity. Currently Suppliers minimise the risk of not having enough electricity by procuring more generation capacity than is required. They consider that delivering a reliable supply is crucial and that the least risky approach is to procure additional supply. DSM could also help Suppliers to balance locally generated renewable electricity within a district. However they cannot be sufficiently confident at the present time that nationally generated load profiles will apply at such a small scale. This may change with data from smart meters.

4.4 Electricity Company DSM Services

The potential DSM service that a group of SMEs could provide was considered alongside the requirements for the existing operator DSM services. The key requirements from the operators were the magnitude of load reduction, the duration of this reduction, the permissible time to respond to a service request and the time between consecutive DSM events. Of the System Operator suite of services, STOR was selected due to its longer response time. It was also noted that STOR is already available via aggregators which would be a key factor for SME participation (section 4.3). No DSM service is available yet from any DNO or Supplier. Of the recent DNO trials of DSM, Western Power Distribution’s Project Falcon was chosen. Detailed information has been published on which to judge its suitability in this research.

4.4.1 Short Term Operating Reserve

National Grid’s requirement for balancing services varies with the season and is different for working and non-working days (National Grid 2014b). To service this requirement, NG defines ‘windows’ when service providers are invited to offer demand reduction (or generation), figure 11. This figure shows the timing of weekday STOR windows for the year from 1st April 2014 to 1st April 2015, referred to as ‘year 8’ (National Grid 2014e). The morning window is generally from 07:00 to 13:30. There is wider variation in the timing of the second window but this is usually from 16:30 to 21:00. With the exception of April 2014, all evening windows covered 17:00 to 18:00.



Source: *National Grid (2014e)*

Figure 11 Short-Term Operating Reserve windows for weekdays from April 2014 to April 2015. The times refer to the start of each settlement period.

STOR contracts are agreed as part of a bid process. A low bid increases the probability of business but reduces the financial benefit. NG does not guarantee any volumes of business to any of its contracted STOR providers. Many companies provide STOR via an aggregator.

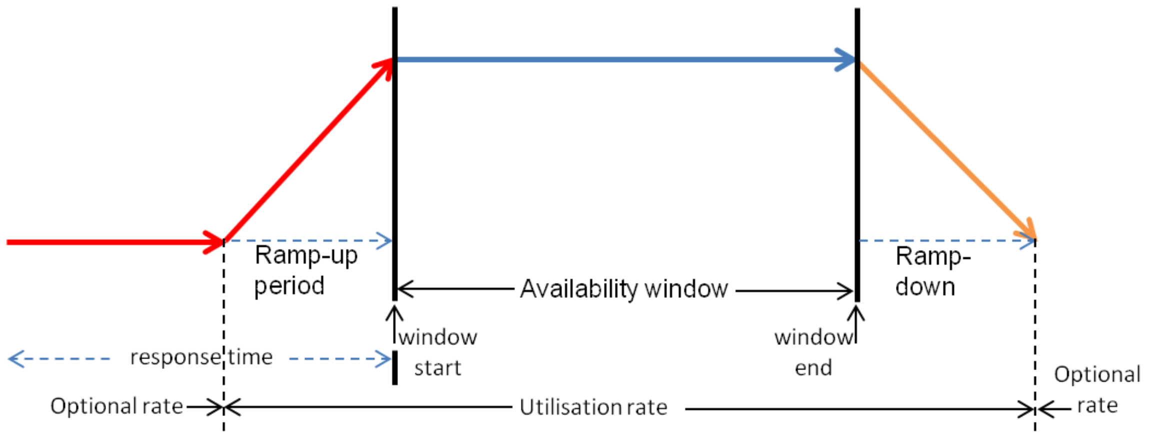
STOR contracts may be ‘*committed*’ or ‘*flexible*’ (National Grid 2014b). Committed service providers must be able to provide service during all of the STOR windows during their contract. Flexible service providers can select which windows they wish to offer a service for. In this research, it was assumed that companies offering a DSM service for the first time would choose the ‘flexible’ service so that they could minimise disruption to their organisation.

A STOR provider must be able to offer at least 3 MW (of load reduction or generation) for at least 2 hours (National Grid 2009). They must be able to provide a service to STOR a second time after an interval of 20 hours. During the year April 2012 to March 2013, the committed service made up the majority of provision during the spring but the flexible service provided over 50% of delivery during the winter when demand was highest (National Grid 2013b). The response time to start supplying STOR service can be up to 240 minutes but NG prefer 20 minutes or less (National Grid 2013a). The vast majority

(98.4%) of STOR units began supplying power in 20 minutes or less in 2012 /13 (National Grid 2013b). 64% of STOR events lasted at least one hour and 21% lasted at least 2 hours.

Demand reduction provides a small proportion of the total STOR capacity; the majority is provided by generators (National Grid 2015b) (National Grid 2015c). Demand reduction accounted for 7% of STOR during winter 2014/15, most of which was supplied under flexible or premium flexible contracts. Most (82%) of this reduction was supplied through aggregators.

National Grid require contracted STOR providers to be able to offer the service at least three times a week (National Grid 2009). The actual frequency of provision may be lower than this, especially for 'flexible' providers who have selected the STOR windows they can provide a service in. One aggregator, Flexitricity, limit STOR provision from generators to 50 hours / year (Flexitricity 2015). No threshold is given for demand reduction. KiWi Power, also a STOR aggregator, state that '*turn down*' of equipment will be for a '*maximum of 30 times per year*' (KiWi Power 2014). They do not comment on the potential impact of turning down HVAC systems on the comfort of building occupants.



Source: *National Grid (2009)*

Figure 12 Timeline of STOR service provision from a generator

With STOR, the instructions are separated into ramp and non-ramp periods, allowing time for a service provider to increase output (National Grid 2009) (figure 12). This is pertinent to generators that may need time to start, synchronise to the grid and increase output. A provider must deliver the full contracted DSM service by the start of the 'availability window'. A provider may start to reduce DSM delivery once NG issues an instruction to ‘cease’ output. The provider’s energy generation (or demand reduction) is measured at one minute resolution.

A STOR provider is paid for ‘availability’ and ‘utilisation’. The availability payment depends on the number of STOR windows which the provider has declared availability less any penalty payments. The availability payment, A_p, is calculated for each settlement period. P_c is the contracted power (MW), C_r is the contracted availability rate (£/MWh), F_f is the failure flag (value of 1 or 0) and M_p is the monthly penalty. The factor of 0.5 is to convert power (MW) to energy for each settlement period (equation 2):

$$Ap = P_c.C_r.F_f.0.5.(1 - M_p/_{100})\ \textbf{(£)} \qquad \text{Equation 2}$$

The ‘failure flag’ is 0 (no payment) for failing to comply with the contract (National Grid 2009). For example if the STOR provider delivers less than 90% of the ‘*contracted volume*’ of energy (MWh) for any settlement period, then this will reduce the availability payment. At the end of each season, the STOR service provided is compared with the energy that NG expected. If a service provider delivers less than 95% of the expected energy within a STOR season, NG will impose a ‘*Seasonal Delivery Reconciliation*’ to ‘*‘claw back’ availability payments by the % of under delivery multiplied by [the] Availability Payment.’* (National Grid 2009) The requirement for 95% availability will be applied in the model to determine the load reduction for each season.

National Grid pay a utilisation payment for the energy (MWh) delivered for the availability window and the ramp periods (figure 12). The load reduction is calculated from the baseline power which is the mean for 4 minutes before a STOR instruction is received. The payment calculation, which was used in this research, is described in section 6.4.2.1.

In this thesis, it was assumed that a group of SMEs would be unfamiliar with STOR and would tender the *flexible* service, allowing them to specify which windows they would provide a service in. Companies tendering successfully for the flexible service are likely to receive lower payments than those offering the committed service. The mean availability payment (weighted by volume and hours tendered) for the flexible STOR service for the year from April 2014 to April 2015 was £1.80/MWh for providers able to operate with less than 20 minutes notice (National Grid 2014c). For providers requiring more than 20 minutes notice, the mean availability payment was £0.65/MWh. The mean utilisation payment for 2014 / 2015, where at least 20 minutes notice was required was £90/MWh (National Grid 2014c). For providers offering less than 20 minutes, the utilisation payments were £139 / MWh.

4.4.2 Demand Side Balancing Reserve

Demand Side Balancing Reserve (DSBR) was introduced by National Grid in Winter 2014 / 2015 to procure additional capacity to balance the transmission network (National Grid 2014a). This is a service that SMEs may be able to offer because the minimum load shift is lower than for STOR, the notice period is normally two hours and it is available through an aggregator. Due to the recent introduction of this service, the benefits to businesses of providing this service have not been evaluated.

4.4.3 DNO DSM Services

DNOs are '*actively exploring a variety of customer incentives and approaches to demand response'* (Ward et al. 2012). DNOs have recently evaluated DSM services, partly funded by Ofgem's LCNF (section 4.3). Due to the 'exploratory' nature of this work and to the location specific requirements for DSM, DNOs do not state generic DSM requirements in either absolute or percentage terms. DSM requirements would depend on the load on an individual sub-station or cable. Western Power Distribution (WPD) give an example in which they consider whether DSM would be a realistic alternative to replacing a transformer. In this case, they suggest 1 MW load reduction might be required at an 11 kV sub-station (Swandells 2014). Northern Powergrid state that DSM '*typically yields 10-15% capacity uplift*' (Sidebotham 2015). The emphasis is on what load reduction might be possible through DSM, rather than on what the DNO would require.

One of the LCNF trials was Western Power Distribution's (WPD) Project FALCON ('*Flexible Approaches for Low Carbon Optimised Networks*') (Swandells 2014). Since one objective of this trial was to evaluate load reduction from commercial customers, it was regarded as informative to this thesis. WPD recruited businesses to participate in a DSM trial directly and via aggregators (Swandells 2014). Their intention was to test both generation and load reduction. The minimum threshold for load reduction was 20 kW and for generation, 100 kW. The load reduction part had to be cancelled as no organisations signed up. A range of reasons were cited including concern over business processes and inadequate compensation for the loss of service.

Project FALCON ran from June 2012 to June 2015 (Swandells 2014). The trial took place within WPD's licence area. This was an area of 150 km^2 covering Milton Keynes and serving approximately 20,000 customers (Jewell 2014). The trials took place over two winters: 2013/14 and 2014/15 (Swandells 2014). At the time of writing this thesis, only the results of season 1 (1^{st} November 2013 to 28^{th} February 2014) were available. Requested 'availability windows' were from 16:00 to 20:00 and the DSM period was for one to two hours. Participants received 30 minutes notice to commence generation of electricity. Up to 40 events were called during the season. Participants were paid £300 / MWh for generation (Swandells 2014). The generator types taking part in the trial included diesel and gas generators, table 15. Most trial participants joined through aggregators, shown in the 'aggregated' columns of table 15. No data were provided on the effect of turning down heating or cooling on building occupants.

Table 15 Quantities of sites with generators participating in Project FALCON Trial, Winter 2013/14

	Diesel		Gas	
	Direct	**Aggregated**	**Direct**	**Aggregated**
Small (<400 kW)	-	5	-	-
Medium (400 – 999 kW)	1	4	-	-
Large (> 1000 kW)	-	1	-	1

Source: *Swandells (2014)*

According to Swandells (2014), the Project FALCON payment to a generator site would be around one third of the net financial benefit to that organisation, table 16. If a 1 MW diesel generator was operated for 40 hours, when requested by Project FALCON, it would avoid the import of electricity worth £3000. If these DSM requests coincided with the 'red band', this would save an additional £3300 (section 4.2.1). If the generation was requested during a green or amber band (for example, due to a fault), this saving would be significantly lower. If the generation coincided with the 'Triad' periods, this would substantially increase the financial benefit (section 4.2.1).

Table 16 Example benefit to a site with a 1 MW generator of participating in DSM for 40 hours with Project FALCON

Description	**Unit price per MWh of generation**	**Sum: for 40 hours**
FALCON payment	£300	£12,000
Electricity import avoided	£75	£3,000
DUoS avoided	£82.60	£3,304
Triad avoided		£25,450
Fuel cost	(£205)	(£8200)
Total		£35,554

Source: *Swandells (2014)*

WPD commented that in order for DSM to be a method they could rely on, DSM has to give greater economic benefit than network reinforcement and achieve similar levels of dependability (Swandells 2014). WPD say '*the benchmark should be in excess of 95% success for both availability and utilisation*' which they add would make it unlikely that they could rely on DSM. This threshold was applied in calculating shiftable load in the multiple building scenarios in section 6.4.2.2.

4.5 Conclusion

The GB electricity network is a hierarchy with defined and regulated roles. Electricity is generated continuously and must be balanced with demand in real time. It is traded with energy suppliers in settlement periods. National Grid as System Operator is responsible for balancing supply and demand. In England and Wales the transmission network is owned by National Grid and the distribution network by DNOs. National Grid and DNOs charge consumers for using their network according to demand. NG's transmission network charges are based on demand during the highest winter peaks; historically these have occurred between 1630 and 1800 on winter weekdays. DNO charges are banded according to time of day; for most DNOs peak charges are 1600 to 1900 on weekdays.

Changes in the generation and consumption of electricity are creating greater challenges for electricity companies. For the System Operator, this is to balance the transmission network at least cost. For a DNO, this is to defer investment in network assets, minimise customer disruption and to avoid over-loading under fault conditions. DSM offers a way to meet these challenges at lower cost. The System Operator has a well developed suite of DSM services for different time periods and size of reduction, to help balance supply and demand. Of these, STOR was considered most suitable for aggregated SME loads. The timing and demand for STOR varies by season. STOR events may be called during pre-defined windows and typically last one to two hours. A requirement for STOR may be fulfilled by demand reduction or local generation and this may be ‘aggregated’ across several organisations in order to meet the minimum requirement of 3 MW. The number of times each year that a company would be asked to provide a STOR service may vary significantly due to pricing and contract. In this thesis, this was considered to be 40 times / year.

DNOs are actively studying the potential for DSM services and carrying out field trials. WPD’s Project Falcon Trial intended to provide DSM from both load reduction and generation but no organisations took part in load reduction. DSM events took place with generators between 16:00 and 20:00 from November to end of February. Each DSM event lasted one to two hours and the total DSM period was 40 hours / year. Energy suppliers are interested in DSM for reducing price volatility but the case is less clear and none have tested any services yet.

The shiftable electrical load from a single SME is likely to be too small to match the requirements of an electricity operator but aggregation across organisations might create a large enough load. Smart grids provide data on time and magnitude of consumption and opportunity to remotely manage demand. A DNO peak load reduction requirement or system operator STOR service may be applicable.

5. Model Background

5.1 Introduction

In seeking to develop a method to quantify DSM opportunities, this thesis identified that SMEs are often small energy consumers. The incentive from energy saving is often small compared with the resource required to implement change. In order to understand energy use in buildings, chapter 3 reviewed classifications of buildings and businesses. This highlighted the inter-related diversity of buildings, businesses and HVAC types. Initial analysis of shiftable loads pointed to thermal loads for space conditioning in offices as the most likely source of load reduction. Loads from a group of buildings need to be aggregated and matched to the requirements of an energy company. Chapter 4 considered the DSM requirements of the energy companies and proposed that a DNO peak load reduction requirement or system operator STOR service may be applicable.

This chapter reviews different modelling methods and proposes an approach applicable to a group of office buildings. The low electricity consumption of many individual businesses suggests that it will be important to analyse the collective load of a group of buildings in order to relate the shiftable load to the DSM requirements of an electricity company. Chapter 6 describes the method used to simulate electrical loads in groups of buildings.

5.2 Modelling Approaches

The need to find enough shiftable load to supply a DSM service suggests that building electricity consumption has to be quantified at the district or cluster scale. Section 5.3 explores how a 'cluster' is envisaged in practice. In this context, the definition of 'model' from The Concise Oxford Dictionary is used: '*a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions*' (Pearsall et al. 1999). Although a model may be implemented in many different forms (physical scale models or software models, for example) a software model is considered here.

Many researchers categorise building energy models as '*top-down*' or '*bottom-up*'. These terms refer to the level of input data aggregation, the outputs that can be expected and the calculations required, table 17. They do not state at what level the analysis is carried out: whether for a single building, a district or a city. A model to support DSM with SMEs is needed to relate to a group of buildings such as a business park (section 3.6). This review considers what may be learned from top-down and bottom-up approaches (sections 5.2.1 and 5.2.2) and then considers examples of district level energy models (section 5.2.3).

The top-down approach is sub-divided into econometric and technological; bottom-up into building physics and statistical. Some models combine approaches. Table 17 summarises their characteristics. Further details are given in (Swan & Ugursal 2009), (Kavgic et al. 2010) and (Zhao & Magoulès 2012).

Table 17 Overview of modelling approaches

	Inputs	**Outputs**	**Calculation**
Top-down	Historical energy or CO_2 for entire building sector *Econometric*: employment, GDP. *Technological*: appliance ownership.	Energy - economy interaction Energy - technology interaction	Fit historical time series of energy data to building stock
Bottom-up building physics	Building geometry & fabric, HVAC, operating schedules, energy consuming equipment	Energy load profiles, disaggregated by end use. Impact of new technologies	Building heat balance & heat gains. Energy consumption in time steps.
Bottom-up statistical	Energy consumption (billing data), floor area, building type	Impact of building occupants on energy consumption	Statistical method (regression, Monte Carlo)

Source: *Swan & Ugursal 2009, Kavgic et al. 2010*

5.2.1 Bottom-up Approaches

Bottom-up models combine data from many disaggregated components, weighted according to their impact on energy use (Kavgic et al. 2010). These models can be used to compare the impact of different carbon reduction options (in carbon and financial terms). There are two distinct sub-types: based on building physics and based on statistics.

5.2.1.1 Building Physics

The building physics category is of particular interest in developing a model to represent groups of SMEs. Building physics models build up an overall picture of energy consumption in one building from each end use, based on measurable data (Zhao & Magoulès 2012). Data from representative buildings of each type are combined to give a stock level model according to the quantity of each type (Kavgic et al. 2010). Large volumes of data are required to describe the building fabric, HVAC system, energy consuming equipment and schedules of operation. This is time-consuming and difficult to collect, especially for existing buildings.

The impact of new technologies, such as heat pumps, can be assessed. Thermal gains can be accounted for from equipment such as computers and the sun. This is the only method that does not rely on historic energy consumption data (Swan & Ugursal 2009). These models do not account well for variations in human behaviour because they rely on physical properties of buildings and occupancy schedules.

Swan & Ugursal (2009) identify three building physics approaches: *archetypes*, *distributions*, and *samples*.

Archetypes

A building physics approach can be applied to a representative set of buildings (Swan & Ugursal 2009). These archetypes are simplifications of actual buildings. Parekh (2005) outlines three steps in the development of archetypal houses for energy simulation: '*geometric configurations'*, '*thermal characteristics'* and '*operating parameters'*. Geometric configuration defines the size and volume, including the shape, the type of roof and the number of storeys. Thermal characteristics relate to property age and building materials. Operating parameters include occupancy patterns and heating schedules. The range of values of each parameter were used to determine the characteristics of each archetype for use in building simulation.

A typology relating to building geometry was described in 3.3.1. This was developed for the NDBS Project and represented non-domestic buildings using three basic types (narrow plan, deep plan and sheds). UK Green Building Council (2007) used these types when modelling energy consumption in existing and planned non-domestic buildings. Office buildings were represented by narrow plan sidelit and deep plan high rise types. These types were also adopted by the Tarbase Project in their study into how to reduce carbon emissions from existing non-domestic buildings by 50% by 2030 (Jenkins et al. 2009).

Korolija et al. (2013) used this work to develop four archetypes to analyse heating and cooling in office buildings. These represent buildings that are open-plan side-lit (type OD), cellular side-lit (CS), artificially lit open-plan (OA) and composite side-lit cellular around artificially lit open-plan (CDO), Figure 17. These four types represent 67% of non-domestic buildings. In each type, office space and common areas are grouped separately. Common space includes corridors, stairs and kitchen areas.

Samples: This method uses energy data from a sample of actual buildings (Swan & Ugursal 2009). The sample has to be large enough to represent all the types, which may make it very expensive and time intensive. By applying appropriate weightings to the sample, the stock level energy may be calculated. This is more difficult to implement with non-domestic buildings than residential due to the greater variety and interaction between activity and building type.

Distributions: This approach uses data on appliance ownership and ratings to calculate energy consumption for each end use (Swan & Ugursal 2009). The end uses are aggregated to estimate the total energy consumption. This does not readily account for interactions between end uses, such as increased demand for cooling from IT equipment.

5.2.1.2 Statistical Approaches

A statistical approach correlates historical energy consumption with other variables (Zhao & Magoulès 2012). The primary source of data are energy supplier bills. A statistical model would relate energy consumption to weather data or determine a building heat loss coefficient. Data from energy bills could be used to calculate typical energy consumption for each property type. This may be attributed to individual end uses, providing that all are considered (Swan & Ugursal 2009). Energy consumption data may be used to calibrate a model and enable it to account for occupant behaviour and economic and social effects (Kavgic et al. 2010).

The diversity in the non-domestic building stock makes it difficult to identify typical energy values for each building type. Energy bills are usually issued only every quarter and are frequently estimated. With existing ‘non smart’ electricity meters, there is no breakdown by end use. The value of this data is in ensuring that the total building energy consumption is accounted for, which may not be the case with a building physics model. Statistical models can generate energy consumption trends providing there are no discontinuities in the physical basis of the model. The lack of data on the building fabric limits the potential for evaluating energy saving measures or new technologies (such as heat pumps).

5.2.2 Top-down Approaches

Top-down models focus on the relationship between the energy sector and the economy (Swan & Ugursal 2009). Typically these models aim to fit historical energy or CO_2 data to the building stock and infer information about it (Kavgic et al. 2010). They are not concerned with end uses of energy and are unlikely to distinguish between building types. Macro-economic trends (such as employment), climate and construction and demolition rates are important inputs. Top-down models may be divided into econometric or technological. Econometric models relate the energy sector to economic output. The focus is on trends observed from the past, not on physical factors in buildings. Technological top-down models seek to explain changes in energy consumption in terms of trends in the building stock such as ownership of appliances.

An advantage of top-down models is that they rely on historic, aggregated energy data (Swan & Ugursal 2009). The total energy consumption is accounted for but caution is needed in attributing it to end uses and building types. The lack of data on how energy is consumed makes it difficult to recommend changes related to behaviour.

5.2.3 District Level Models

This section considers the following questions: 'How can *a modelling approach for SME DSM be informed by existing district level models?'* and '*To what extent does a building's neighbours affect the first building's energy consumption?*'. Existing district level models are reviewed and their applicability to a multiple office building model in the UK are considered.

Yamaguchi et al. (2007) proposed a '*district clustering modelling approach*' to identify archetype districts which could be combined to represent city level energy. A 500m x 500m grid was overlaid on the city and each cell was allocated one of six district categories. These categories related to the building floor areas, building heights, building density and business activities (such as office, retail and hotel). A representative grid cell in each category was selected and all buildings over 1000 m^2 were surveyed in order to determine the breakdown of buildings by floor area category. This approach would be very labour intensive if all larger buildings have to be surveyed. The reasons why the authors selected specific areas as 'typical' is unclear, which makes it difficult to apply elsewhere. In a town such as Reading, a small area contains many buildings of different ages, types and uses.

Heiple & Sailor (2008) developed a method to generate temporal energy consumption profiles for each grid cell of a city. The authors simulated annual energy consumption (kWh/m^2.yr) for 11 prototype buildings and compared these with data from government sources. Daily consumption profiles were generated by calculating the mean for each hour for a given building, with each month or season. These were scaled by building data in GIS format and compared with top-down energy consumption disaggregated to city level. The authors generated energy consumption profiles for each grid square at 6-hour intervals. The authors found that building density was a more critical factor in governing the magnitude of the heat flux than the mixture of building types. Heiple & Sailor (2008) did not distinguish building age bands. In order to apply this approach in Reading, would need to have prototypes for each building type, or detailed survey data for every building in the study area.

Jones et al. (2007) developed the Energy and Environmental Prediction (EEP) model to represent energy use at the urban scale using GIS data and '*drive by surveys'*. Non-domestic and domestic buildings were included. Ordnance Survey (OS) Mastermap™ data provided floor area and façade dimensions and data on built form was derived from surveys. It is unclear how spatial data on non-domestic buildings was to be correlated with energy consumption data, except at the local authority level.

Futcher & Mills (2013) examined the effect of urban form on energy consumption by examining cooling loads in office buildings in Central London, which were driven by solar irradiance. The authors found that for a stand alone building, the form or orientation was '*of little consequence'* to the energy consumption. However in an urban setting, shading had site specific effects related to the arrangement of buildings on the street. This effect becomes increasingly important in the future as regulated loads are reduced by efficiency improvements. Salat (2009) proposed that the layout of buildings in an urban area can affect energy consumption. Buildings in Paris constructed during the mid 20th century consumed 1.8 times more energy for heating than 19th century or late 20th century buildings. This was partly due to high solar gain.

5.3 SME DSM and Electricity Company Requirements

The requirements of National Grid's STOR service and of a DNO DSM trial service were described in sections 4.4.1 and 4.4.3. This section relates this to what SMEs may be able to offer. Table 18 summaries the requirements of the stakeholders and key parameters. SME interest in energy is in reducing costs, generating income and gaining customers through good environmental management (section 2.5). DSM may offer income from time shifting of flexible loads or reduced bills from lower usage during peak periods. Flexibility is only possible providing comfortable conditions are maintained in the building. The system operator (SO) is mandated to balance supply and demand at least cost and to maintain the system frequency within a small tolerance (section 4.2). DNOs are concerned with keeping the loads through their plant within operating limits (section 4.3). Energy suppliers are concerned with reducing risk from wholesale electricity costs and maximising revenue (section 4.3).

Table 18 DSM Stakeholders and Requirements

Stakeholder	Requirements	Parameters
SMEs and landlords	Reduce energy bills or gain income Thermal comfort Gain or retain customers	Payment or reduced energy bills Employees are comfortable
SO	System balancing	System frequency Supply voltage within limits Minimise cost
DNOs	Peak load reduction; defer network investment	Current and voltage to customers within permitted limits
Energy supplier	Reducing risk from wholesale costs	Maximise revenue

The System Operator DSM service identified as relevant to SME loads was STOR. STOR requirements are largely non geographic although greater demand in south and more supply in the north.

Peak demand reduction would help a DNO with peak load reduction but only trials have been carried out. DNO peak load reduction requirements are very location specific – each requirement related to the peak load on the sub-station and cables. The DNO requirement for peak load reduction would apply in a small geographic area, focused on the plant under investigation.

A building cluster could consist of a group of buildings which are spatially close (geographical cluster) or similar buildings that are physically separated. In either case, the discretionary load has to be aggregated. These approaches are compared in table 19. The geographic approach focuses on the buildings in a small area, such as a business park. These are likely to be similar in type and age and may contain related business activities. The energy consumption of all organisations in this area has to be accounted for although SMEs are the focus for load-shifting. This approach relates to the needs of the DNO by aiming to reduce peak loads. With a non-geographic cluster, representative building types are modelled in diverse locations. Each building has one primary activity type (such as commercial office). Load-shifting would benefit the SO by supporting system balancing.

Table 19 Comparison of geographic and non-geographic clustering

	Geographic cluster	**Non-geographic cluster**
Location	Buildings situated in a tight geographic area (such as a business park)	Buildings in several disparate locations
Property type	One main building type with variations (geometry, insulation, fit-out)	Select a few representative building types
Business activity	High variation but some commonality (businesses with related interests)	One primary activity type for each building type
Consumption profile	Covers all organisations present in specified area	Covers occupiers of designated buildings only (mainly SMEs)
Client	DNO: peak avoidance	SO: system balancing

The model must quantify parameters of shiftable load that indicate its suitability as a service for different stakeholders.

5.4 Requirements for an SME cluster model

This section describes the requirements for a cluster model and relates these to existing modelling approaches. A cluster model must represent building electricity consumption as a time series. The time interval is a compromise between the need to capture important events and having a manageable dataset. It should be fine enough, that the transient effects of reducing heating or cooling loads are evident. Occupant schedules should be represented with sufficient granularity to show the effect of switching off cooling or heating. Electricity consumption must be disaggregated by end use, such that shiftable loads can be calculated.

The end uses with potential for load-shifting must be disaggregated; other uses could be combined. The business activity in each building will be represented at the high level of 'office'. The representation of the building fabric should enable the effect of different building age bands on the discretionary load to be estimated. It should be possible to test the effect of energy saving measures or the effect of thermal mass.

Wright (2005) describes the requirements for an energy modelling tool for the non-domestic stock as part of the Carbon Reduction in Buildings Project (CaRB). Table 20 compares the criteria used by Wright (2005) (left column) with those proposed for an SME cluster model.

Table 20 Key factors for building energy modelling

Non-domestic model (Wright 2005)	**SME Cluster Model**
Level of detail	Level of detail (cross-cutting)
Geometry	Geometry
Thermal fabric properties	Building fabric
Ventilation	Energy
Lighting	Energy
Equipment	Energy
Occupancy and temperatures	Business activity
Miscellaneous services	Energy
Weather data	Weather data
	Timescale (cross-cutting)

For an SME cluster model, the factors in the right column of table 20 are used. Level of detail is a cross-cutting theme. Since the focus is on thermal loads that can be time-shifted, energy consumed by HVAC equipment is identified within the energy category, which is disaggregated by end use. Most of these factors and especially HVAC are analysed in relation to time of use (peak or off-peak).

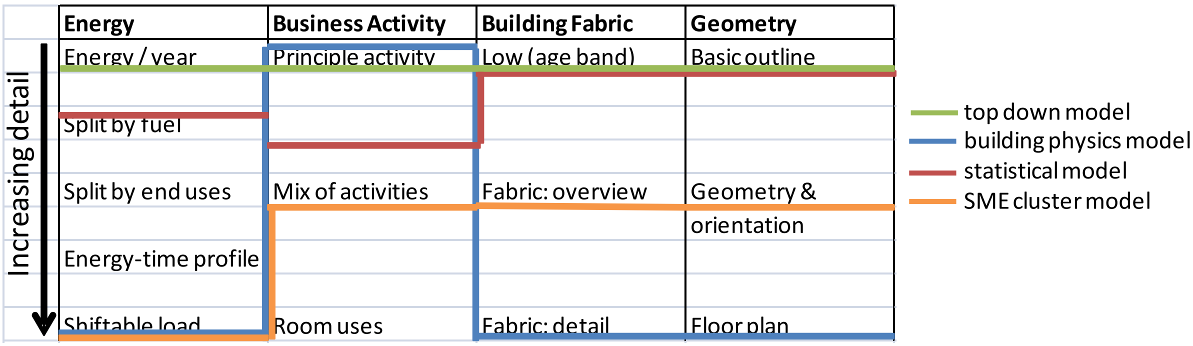


Figure 13 Comparison of level of detail in different modelling approaches

The existing modelling approaches (section 5.2) are compared with a possible SME cluster model in figure 13. The four columns (energy to geometry) represent the major requirement themes. The rows express each factor with increasing detail (from top to bottom). The coloured lines represent the typical level of detail expected with each model type. For example, a building physics model (blue line) would identify the shiftable load, would ‘know’ almost nothing about the business activity but would ‘know’ the detailed building fabric and the detailed floor plan.

Analysis of the existing modelling approaches points towards a building physics model with a reduced set of parameters. A top-down approach is attractive because the data requirements are un-demanding and the output takes account of economic or technological trends. However, this does not account for discontinuities, such as new technologies. Typically it is not possible to disaggregate electricity consumption from a top-down approach into end uses, which is key to load-shifting. A bottom-up building physics approach accounts for end-uses of electricity and can show the effect of new technologies such as heat pumps, which could offer new discretionary loads. Inputs to such a model account for the building fabric, HVAC and other end uses. Occupancy schedules account for human behaviour to a limited extent. The data requirement for a cluster of buildings is huge, unless the requirements are simplified. Section 6.2 describes how this has been achieved in this model. A building physics approach might under-estimate the total energy consumption, if some end uses are under-represented. A statistical approach will account for these and might provide useful verification, especially at the whole building level. The focus of this work is that the building fabric has enough thermal inertia to maintain a comfortable environment while the heating or cooling system is not operating for short periods. The thermal loads for a cluster of buildings will be related to the HVAC and occupancy schedules but will be smoothed by aggregation.

Archetypes are used to reduce the number of simulations for a geographic cluster. The chosen geometric types (figure 17) are combined with three age bands and two HVAC types (section 6.3.3). A statistical overlay using historic energy bills validates this by confirming that all electricity is accounted for and allowing for variation in human behaviour.

The loads best suited to time-shifting are electrical space heating and cooling (Dolman et al. 2012) (Ward et al. 2012). The thermal inertia in the building fabric should allow the heating or cooling to be switched off for short periods before the internal temperature exceeds the acceptable thresholds (too hot or too cold). The acceptable duration without heating or cooling and the size of the shiftable load, compared with ‘business as usual’ (no load-shifting) are important.

5.5 Conclusion

This chapter has reviewed existing approaches to modelling energy consumption in buildings and related them to the requirements for an SME group model. A model that represents a group of buildings with the aim of quantifying DSM opportunities requires time series data of electricity consumption. The end uses with DSM potential must be individually visible at a time resolution consistent with the load shift period. The loads most relevant to DSM within offices are space heating and cooling.

Top-down approaches are good for assessing trends but do not provide detailed knowledge of the energy-time-temperature profile and load-shifting potential in clusters of buildings. A bottom-up building physics approach takes account of the building fabric, new technologies, end uses of energy, building geometry and time profiling which all affect energy consumption. This approach does not account for changes in behaviour. A large number of inputs are required and making them compatible is a challenge. The use of built form types simplifies the simulation. Statistical approaches which rely on historic energy bills help to account for total energy consumption but will not account for discontinuities in future energy demand.

A review of district level models highlights approaches which would be difficult to apply with non-domestic buildings in the UK. Due to the heterogeneity of the stock, it is not feasible to characterise the buildings in one district with a single type. The diversity of building ages, types and activities within a small area makes it necessary to survey a large proportion of the buildings. The effect of urban morphology could affect energy consumption by 2 to 3 times due to shading but this is likely to be site specific.

6. Modelling Method

6.1 Introduction

To quantify DSM potential from SMEs, it is necessary to identify flexible loads with respect to time. Chapter 2 established the diversity of non-domestic buildings occupied by SMEs and that individual companies are often low energy users. The following chapter looked at ways to classify buildings and businesses and at annual energy consumption, on a static basis. This pointed to heating and cooling in office buildings as being the main loads to consider. Temporal profiles which identify flexibility within end uses are needed to quantify DSM. Chapter 5 reviewed different approaches to modelling reported in the literature and proposed a building physics approach with a reduced parameter set and a statistical overlay.

The objective of this chapter is '*to develop a method to estimate the discretionary electrical load from a group of buildings, using simulations of individual buildings'*. The requirements of this model are considered in relation to the electricity company stakeholders. The role of this model in this research is described. A model of a single office building is developed first and then used to develop the multiple building model. The single building model uses 24 cases to represent built form, age bands and HVAC types with a range of values assigned to parameter to represent differences between buildings. The implementation of the model and process flow are described. Tests to check the reasonableness of the results are described. The multiple building model is developed and test scenarios which relate to DNO and SO requirements are described.

6.2 Role of a Building Model in this Research

The purpose of this model was to estimate the technical potential for time-shifting of electrical heating and cooling loads from groups of buildings. This was developed from representations of individual buildings. The model focused on offices since this typology is widely represented and is one of the most energy intensive in the commercial sector (Perez-Lombard et al. 2008). 'Offices' is the largest building category in Reading Borough (section 3.5.4) and a significant amount of comparison data exists in the literature.

The model of groups of buildings was developed using archetypes of individual buildings. The role of the single building model was to represent electricity use in one building, as a time series in order to quantify *shiftable load*. The simulations concern DSM by load reduction only, rather than local generation (section 4.4). The most suitable *shiftable load*s are heating and cooling (section 3.4.3); these alone are considered. The buildings represented are offices. DSM was estimated by setting back heating to a lower threshold (and cooling to a higher threshold). The multiple building model was developed to quantify *shiftable load* in a group of buildings and then relate this to the requirements for SO balancing services or DNO peak reduction.

The shiftable load was estimated by reducing the heating and cooling for 1 hour each weekday. Initially heating and cooling were changed to the setback levels applied during evenings and weekends but this resulted in temperatures as low as 16°C in the 1970s fabric buildings during December. As noted in section 6.3.8, heating and cooling were setback to 19°C and 26°C respectively during load shift periods, to maintain adequate comfort. The modelling software gives a deterministic output which does not represent variation across buildings. In order to represent this, some variation was introduced with key parameters given a range of values (section 6.3.5). 24 building cases which combined building type, age band and HVAC were developed (section 6.3). These were simulated for one year and the business as usual (BaU) results compared with benchmark data. The building cases were amended and the simulation re-run for BaU and load-shift scenarios. Three multiple building scenarios were developed (section 6.4.1). The building cases were simulated for a group of buildings in an area of Reading and the shiftable load was calculated.

6.3 Development of the single building model

This model represents energy consumption in office buildings, with separate end uses evaluated as time series. An approach was developed to quantify electrical loads that could be shifted in time away from peak periods in response to requests from the DNO or System Operator. The largest flexible loads in office buildings were identified as heating and cooling (section 3.4.3). The current building stock in England and Wales was broadly categorised into: buildings with gas heating, electric cooling and mechanical ventilation (54%), those with gas heating and natural ventilation (36%) and those with electric heating (10%) (section 3.5.3.1). The first group (54%) has the largest potential for load shifting due to the cooling and ventilation being electrically driven; these were represented in the *current* scenario. Buildings with electric heating were excluded since most is either '*Economy 7*' for which further load shifting is unlikely or heaters with no central control (section 3.5.3.2). A shift to low carbon heat such as heat pumps will be required to meet the UK Government's targets for carbon reduction (National Grid 2015a). Air source heat pumps represent one such technology which can be retrofitted into existing buildings and which offers greater opportunities for DSM. The potential impact on the existing office building stock is illustrated in the *alternative* scenario. This was an illustrative scenario in which electric heat pumps replaced gas heating in all buildings constructed up to the year 2000 but no changes were made to the fabric, internal equipment or activity schedules.

The current and alternative scenarios represented office buildings constructed up to the year 2000. These were applied to the building stock in Reading. The *current* scenario modelled the segment of the present day stock with gas heating, electric cooling and mechanical ventilation. The *alternative* scenario represented office buildings in Reading up to the year 2000, assuming that heating and cooling were provided by air source heat pumps (ASHPs). The portions of the building stock represented by these two scenarios are illustrated in figure 14 and figure 15. The HVAC proportions (section 3.5.3.1) were combined with the building age bands for Reading Borough (section 3.5.4). The built form types and HVAC types were assumed to apply equally to each building age band. The HVAC type is shown on the horizontal axis and the age band on the vertical axis. The proportion of office buildings with gas heating, cooling and mechanical ventilation was estimated as 54% (section 3.5.3.1). Office buildings in Reading constructed before 2001, accounted for 83% by floor area (section 3.5.4). The *current* scenario represents 45% (0.54 x 0.83 = 0.45) of office buildings in Reading.

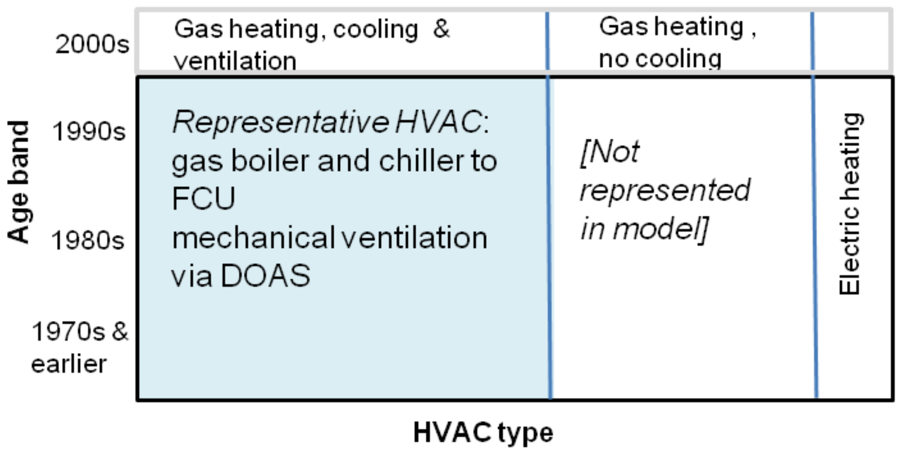


Figure 14 Office buildings in the *current* scenario for Reading Borough, disaggregated by age band and HVAC type

The *alternative* scenario illustrates the effect of all electric HVAC systems in existing office buildings on the potential for DSM. The HVAC systems in all pre-2001 buildings were ASHPs. The only upgrades to the building fabric were to permit mechanical ventilation. No changes were made to occupancy or activity schedules. This is illustrated by figure 15. The blue shading relates to the sector of the building stock that this scenario represents: all pre-2000 office buildings (83%).

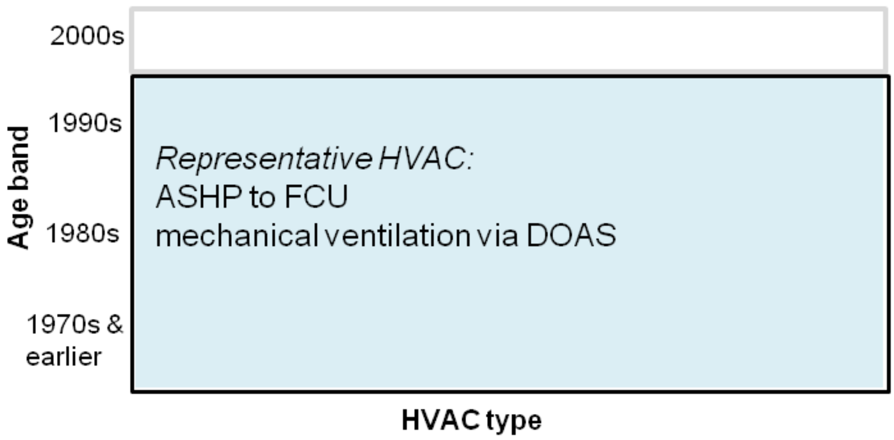


Figure 15 Office buildings in the *alternative* scenario for Reading Borough, disaggregated by age band and HVAC type

In both scenarios (*current* and *alternative*), four built form types were used to represent plan depth and the allocation of internal space. These are described in section 6.3.1 below. The model used three age bands to represent different levels of fabric heat loss; these are described in section 6.3.2. One representative HVAC type was modelled in each of the current and alternative scenarios. This constituted 24 model cases (4 types x 3 age bands x 2 HVAC types) figure 16.

The building types, age bands and HVAC types in the Business as Usual (BaU) scenario are described in sections 6.3.1 to 6.3.3. Occupancy schedules, lighting levels and other internal building factors are detailed in section 6.3.4. Key parameters were assigned a range of values to represent differences in activity (section 6.3.5). The software implementation of this model is described in section 6.3.6 and the steps taken to verify it was functioning as intended and that the output was reasonable are described in section 6.3.7. The load shift scenario is developed in section 6.3.8. The process of comparing modelled data with external sources and sensitivity testing is described in sections 6.3.9 and 6.3.10.

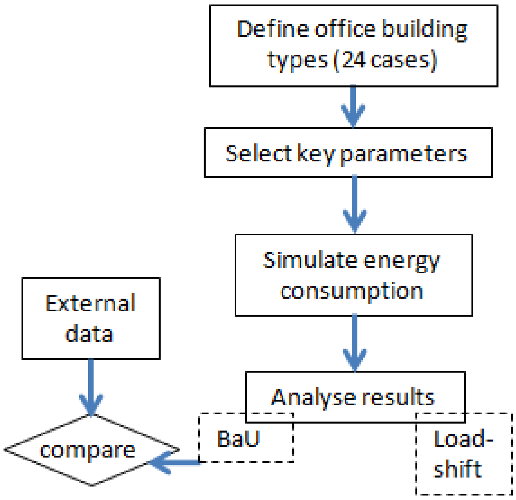
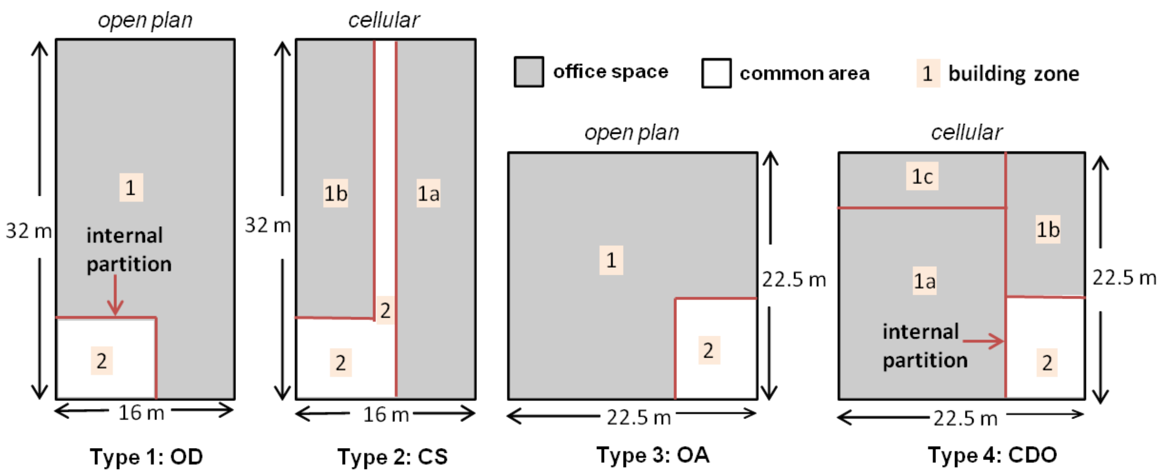


Figure 16 Process for modelling single buildings

6.3.1 Building Types

The four built form types represent 67% of non-domestic buildings, (table 4 in section 3.3.1). They represent plan depth (narrow and deep) and allocation of space (open plan and cellular) (section 3.3.1.). These types, shown in figure 17, are identical to those used by Korolija et al. (2013). Types 1 and 3 are open plan; types 2 and 4 are cellular. Office space is shown in grey and common areas in white.



Source: *Korolija et al. (2013)*

Figure 17 Built form types represented in this research

Office working space and common areas were grouped into separate zones to account for different levels of occupancy and heat gain. The common areas in each type, consisted of non-productive space, such as, stairwells, corridors and toilets. These areas were grouped into a single zone on each floor, indicated by the 'building zone' numbers on figure 17 (indicated by zone 2 in all types in figure 17). Within each floor, adjacent zones are separated by internal building partitions, shown by the red lines in figure 17. Each partition consisted of two layers of gypsum plaster separated by an air gap (section 6.3.2). The thermal mass of these partitions was modified to test the effect on the shiftable load in section 6.3.10.3. The areas of these zones are given in table 21.

Table 21 Archetype floor areas, used in model. Based on *Korolija et al. (2013)*

Type	Office space			Common area			
	Zone 1a (m^2)	Zone 1b (m^2)	Zone 1c (m^2)	Zone2 (m^2)	Floor area, GIA (m^2)	Bldg area, GIA (m^2)	Bldg area, GEA (m^2)
Type 1 OD	421.2			63.0	484	1452.6	1536
Type 2 CS	201.1	170.9		112.3	484	1452.6	1536
Type 3 OA	418.0			62.2	480	1440.7	1518.75
Type 4 CDO	223.7	105.0	89.3	62.2	480	1440.7	1518.75

Each built form type has three floors in order to represent differences in energy exchange between the building and its environment (Korolija et al. 2013). The dimensions in figure 17 are external dimensions for each floor and were entered in DesignBuilder (section 6.3.6) when defining the building types. Table 21 records these as ‘Bldg area, GEA’. Gross internal area (GIA) is the floor area less the thickness of the external walls (VOA 2012b).

6.3.2 Building Envelope and Age Bands

Age was regarded as a proxy for the thermal efficiency of a building (section 3.5.2). Taking the analysis of office floor areas in section 3.5.4, three age bands were chosen which represented office buildings constructed during 1970s or earlier until the end of the 1990s. Buildings constructed during 1970s or earlier were represented by type F1, those constructed during 1980’s (type F2) and those constructed during 1990’s (F3), table 22. Type F1 relates to pre-1980 property with no insulation and single glazed windows and relates to buildings in the ‘1965 / 1972’ column of table 9 in section 3.5.2. This makes up 25% of office space in Reading Borough (section 3.5.4). During this era, The Regulations were introduced for thermal efficiency and were assumed to have a gradual impact on non-domestic property. Type F2 represents offices constructed during 1980’s and accounts for 35% of building floor area. These have low levels of insulation and would comply with Part L 1985 (Parliament 1985). Type F3 represents offices constructed during 1990’s, estimated to be 23% of the office building stock (section 3.5.4). These comply with The

Building Regulations, Part L 1995 (DEWO 1995). Buildings constructed after 2000 were not represented since the build rate was lower.

The glazed area was entered into DesignBuilder as window to wall ratio (WWR). This was assumed to be 50% for all walls (Korolija et al. 2013). The glazing was assumed not to have any coating or external shading to reduce solar gain.

The construction of external walls, roof and ground floor are detailed in Appendix A. Adjacent building zones were separated by internal partitions, which consisted of two layers of gypsum plaster (25 mm each) separated by a 100mm air gap. This was the same for all age bands. A sensitivity test was carried out to determine the effect of changing the density of the plaster and replacing it with concrete (section 6.3.10.3).

Table 22 Building fabric values used in simulations

Fabric type (F)		F1: 1970 or earlier	F2: 1980's	F3: 1990's	Reference
External wall	U-value ($W/m^2.K$)	1.50	0.54	0.45	(Parliament 1965), (Parliament 1985), (DEWO 1995)
Flat roof		2.59	0.43	0.25	
Ground floor		1.07	0.82	0.45	
Glazing		5.70	3.3	1.96	
Light transmission		0.82	0.74	0.74	(Korolija et al. 2013)
SHGC		0.68	0.69	0.69	
Window to wall ratio		50%	50%	50%	
Glazing coating		No	No	No	
Shading (overhang)		No	No	No	
Infiltration	ACH	0.7	0.5	0.3	

SHGC: solar heat gain coefficient
ACH: air changes per hour

6.3.3 HVAC and DHW

In the present day office building stock, no HVAC system type can be exclusively associated with any particular building type (section 3.5.3.1). In modelling these buildings, one representative HVAC type was chosen. In the *current* scenario, the primary systems were gas boilers and electric chillers. In the *alternative* scenario, the primary systems were Air Source Heat Pumps (ASHP). In both scenarios, the secondary system was an outdoor air system (DOAS) with variable flow fan, figure 18. These systems are described in sections 6.3.3.1 and 6.3.3.2.

These HVAC systems provided heating and cooling for the segment of the current building stock that has gas heating, electric cooling and mechanical ventilation (shaded blue in figure 14). The life expectancy of HVAC system components was based on data from BSRIA which states 20 years for boilers and pumps, 30 years for chillers and 15 years for air handling units (Churcher 2014). In this research, the boilers, chillers and ventilation systems originally installed in each building were assumed to have life expectancies of 20 years and to have all been replaced.

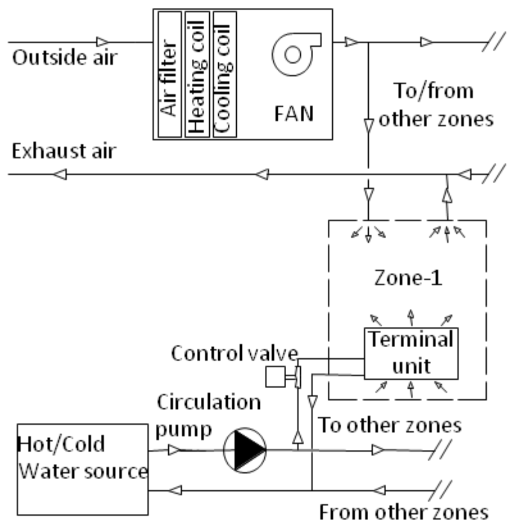


Figure 18 Modelled HVAC system consisting of a heating and cooling source and a dedicated outdoor air system with a variable flow fan providing ventilation (source: *Shahrestani 2013*).

6.3.3.1 Current Scenario HVAC

In the current scenario, the primary HVAC system in figure 18 was a gas boiler and chiller. The secondary system was a dedicated outdoor air system (DOAS) with a variable flow fan. Heating and cooling of the occupied space were provided by a natural gas boiler, fan coil units and a chiller. Heated water was supplied to 4-pipe fan coil units. Cooling was supplied by a vapour compression cycle air cooled electric chiller (BSI 2013). DOAS is responsible for the supply of outdoor air for ventilation to the occupied space (Dieckmann et al. 2007). The DOAS filters the outdoor air and provides temperature adjustment. The outdoor air is sent to each space after treatment through a heating and cooling process to provide thermally neutral fresh air. This was supplied to the occupied space via a variable flow fan, which provided sufficient air to satisfy ventilation requirements.

During load shift periods, the heating and cooling demands were reduced but the ventilation requirement was unchanged (section 6.3.3.4). Fan energy for ventilation was determined by the number of occupants in the building, which was constant during the load shift periods.

6.3.3.2 Alternative Scenario HVAC

In the *alternative* scenario, the source of heating and cooling in figure 18 was an air source heat pump. Ventilation was provided by the DOAS.

6.3.3.3 Implementation of HVAC in Model

The HVAC system was represented as an 'ideal' system that calculated the heating and cooling loads for each timestep based on the model input data. The heating and cooling loads were multiplied by fixed coefficient of performance (CoP) values to determine the fuel inputs (gas and electricity).

Table 23 HVAC fuels and CoPs for the *current* scenario

Age band	**Heating:** gas boiler		**Cooling:** vapour compression cycle chiller		Reference
	fuel	**efficiency**	**Fuel**	**CoP**	
1970s	gas	0.84	electricity	2.25	DCLG (2006)
1980s	gas	0.84	electricity	2.50	HM Government (2010b)
1990s	gas	0.84	electricity	2.55	HM Government (2014)

The minimum efficiency of gas boilers and chillers has increased with successive revisions to '*The Building Services Compliance Guide*'. The model assumed that the lifespan of the HVAC systems in the modelled buildings was 20 years meaning that the systems installed at the time of construction had all been replaced (section 6.3.3). In the *current* scenario, the buildings constructed during the 1990s were assumed to comply with the most recent edition of '*The Non-Domestic Building Services Compliance Guide*', (HM Government 2014) and the oldest buildings with the 2006 edition (DCLG 2006). This was reflected in higher CoPs for cooling in the 1980s and 1990s buildings (table 23). The thermal losses through distribution pipes are not included.

In the *alternative* scenario, all buildings were assumed to have ASHPs which complied with the 2014 edition of '*The Non-Domestic Building Services Compliance Guide*', (HM Government 2014). The heating system efficiency and cooling CoP values are given in table 24.

Table 24 HVAC fuels and CoPs for the *alternative* scenario

Age band	**Heating:** ASHP		**Cooling:** ASHP		Reference
	fuel	**CoP**	**fuel**	**CoP**	
All	electricity	2.50	electricity	3.2	HM Government (2014)

The HVAC system was modelled as a convective air system with heat recovery (DesignBuilder 2011, p.230). The required air flow and temperature were calculated using the EnergyPlus '*purchased air*' model (EnergyPlus 2012, p.963). The heating was controlled by the '*operative*' temperature. This gives equal weight to the mean air temperature and the mean radiant temperature (DesignBuilder 2011, p.319). Control using the operative temperature was chosen in preference to air temperature in order to give time for the building to become comfortable and the temperature of the building fabric to increase. Simulations with the control set to 'air temperature', resulted in very rapid fluctuations in temperature. This was due to the air being warmed but not the fabric and contents of the building.

6.3.3.4 Ventilation and Auxiliary Energy

'Auxiliary energy' is the energy consumed by HVAC fans and pumps (BRE 2014b). In an HVAC system, this may account for a significant proportion of the building annual heating and cooling demand (Korolija et al. 2011), (Shahrestani et al. 2013). In this research, 'fan energy' represented the sum of energy for ventilation (through the DOAS) and energy for distributing warm and cool air (via FCUs). The requirement for outside air in each building zone was determined by the occupancy schedule (figure 19).

The mean specific fan power (SFP) was used to check the model output values for fan power (section 6.3.7.1). The SFP values used were taken from '*The Non-Domestic Building Services Compliance Guide'* and are given in table 25. The assumption, stated above, that the 'original' HVAC systems had been replaced was used to inform the choice of fan SFP values. The 1970s buildings had fans that complied with the 2006 Edition, (DCLG 2006) and the 1990s buildings with the 2014 Edition (HM Government 2014). Variable speed fans were assumed in all buildings.

Table 25 Specific fan powers in the *current* scenario

Building age band	**Fan SFP** (W/l.s) DOAS	FCU	**Mean SFP** (W/l.s)	Reference
1970s	2.0	0.8	1.4	DCLG (2006)
1980s	1.6	0.6	1.1	HM Government (2010b)
1990s	1.6	0.5	1.05	HM Government (2014)

In the *alternative* scenario, all buildings complied with the 2014 Edition of '*The Non-domestic Building Services Compliance Guide*'. The fans were variable speed with a mean SFP of 1.05 W/l.s. The pump power density was determined by the heating and cooling schedule since this supplied heated or chilled water in response to system demand. Pump power was calculated using the pump power density and the heating schedule fraction. The pump power density was 0.9 W/m^2 (BRE 2014b) for all model cases and was reduced by half during load shift periods.

6.3.3.5 Domestic hot water (DHW)

In the *current* scenario with gas heating, the domestic hot water (DHW) was produced by the gas boiler and stored in a central cylinder. The DHW system efficiency was the same as for the space heating system (84%, table 23). In the *alternative* scenario (with electric heating) DHW was produced and stored in a central hot water boiler. The overall thermal efficiency of the system, allowing for heat losses was 96%.

Table 26 Area of office space used in calculation of DHW volumes (based on: *Korolija et al. (2013)*)

	Building internal area, GIA (m^2)	**Office space (m^2)**
Type 1	1453	1264
Type 2	1453	1116
Type 3	1441	1254
Type 4	1441	1254

For DHW, BSRIA's '*rule of thumb*' of '*maximum daily hot water consumption for offices without canteens*' is 10 l/person.day (Hawkins 2011). This value was initially used in simulations but the annual energy consumption for DHW was higher than seemed reasonable, especially for open plan types (1 and 3). The DHW requirement was calculated from the office area only and assumed to be zero in common areas, table 26. The consumption rate was adjusted to 8 l/person.day in open plan types (1 and 3) and 10 l/person.day in cellular types (2 and 4). Mains water was drawn in at 10°C and heated to 60°C (BRE 2014b). The timing and volume of hot water production were determined by the occupancy schedule (figure 19).

6.3.4 Indoor Environment

The modelled buildings were occupied on weekdays with only a few staff present at weekends. On weekdays, office and common areas were fully occupied from 09:00 to 12:00 and 14:00 to 17:00 (figure 19). Prior to 07:00 and after 19:00, weekday occupancy was zero. Between 07:00 and 09:00, occupancy was stepped up by 25% each hour and stepped down at the same rate between 17:00 and 19:00. Between 12:00 and 14:00, occupancy was reduced by 25%, due to lunch breaks. At weekends, it was assumed that the mean occupancy would be low, based on the whole stock in Reading. The weekend occupancy in office space was 10% and zero in common areas. It was assumed that local heaters would provide heating during weekend working. The occupancy profile was used to schedule building ventilation and domestic hot water (DHW).

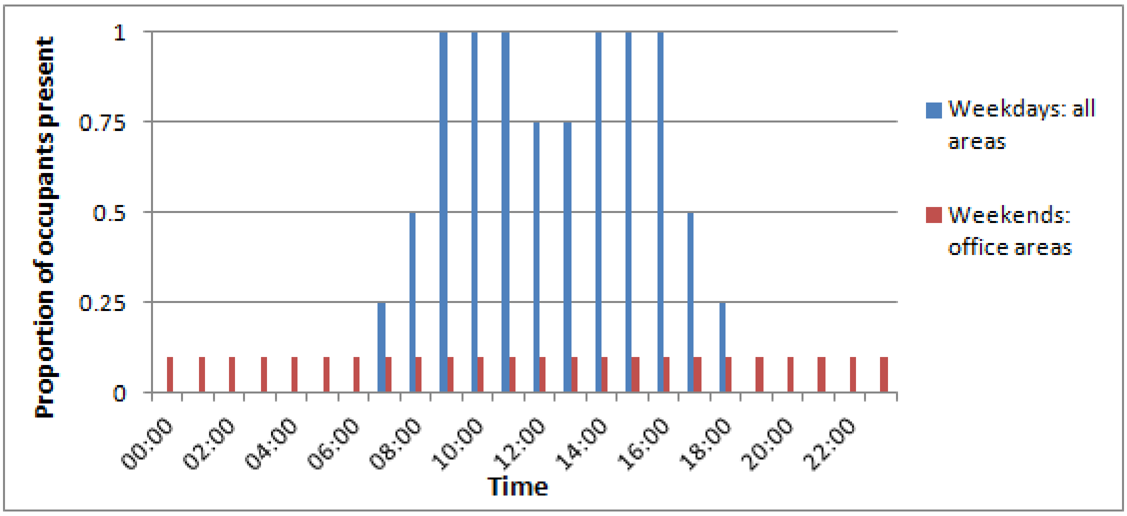


Figure 19 Occupancy fraction for weekdays and weekends used in simulations. Based on**:** *Korolija et al. (2013)*

The heating and cooling setpoints were based on the winter and summer operative temperatures for offices specified by CIBSE (CIBSE 2015, section 1.5). These are 21°C to 23°C in winter and 22°C to 25°C in summer in buildings with air-conditioning. This is similar to the temperatures recommended by British Council for Offices (BCO) which are 18 to 22°C in winter and 22°C to 26°C in summer in buildings with air-conditioning (BCO 2014). The chosen setpoints in this research were 21°C to 23°C for heating and 22°C to 24°C for cooling, table 28. For each simulation, a pair of integer values for heating and cooling were chosen to reduce the possibility of simultaneous heating and cooling (section 6.3.5). Common areas represent non-productive space, so these setpoints were regarded as less critical. These were fixed at 21°C for heating and 25°C for cooling.

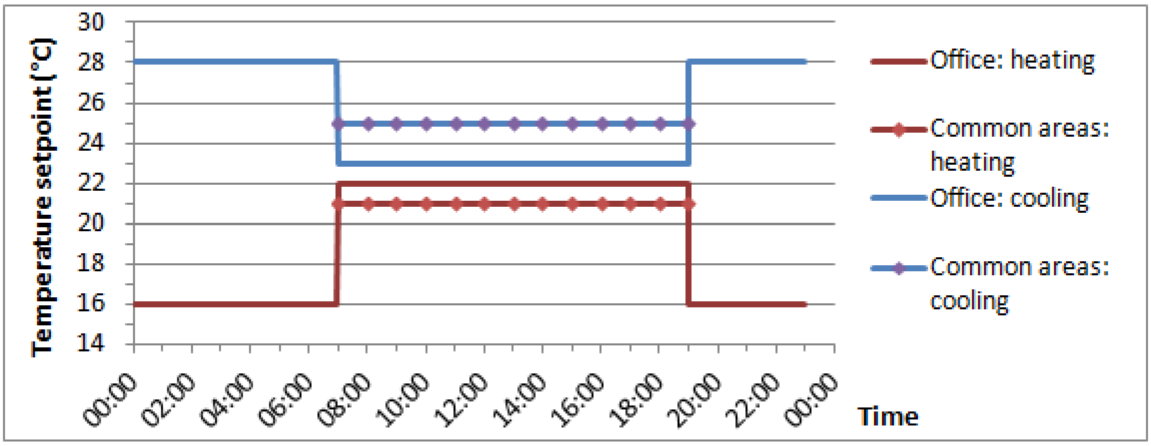


Figure 20 Heating and cooling levels in simulations on weekdays. Based on**:** *CIBSE (2015)*

In some buildings the heating is 'setback' to a low level outside normal working hours to avoid condensation and frost damage (Korolija et al. 2013). In the BaU scenario, the heating was setback to 16°C; this is the minimum level for workplaces specified in The Workplace (Health, Safety and Welfare) Regulations 1992 (HSE 2013). The setback level for cooling in the BaU scenario was 28°C. This was consistent with the '*traditional*' approach taken by CIBSE that the '*internal operative temperature should not exceed ... 28°C for more than 1% of occupied hours*' (CIBSE 2015, section 5.10). This value is also recommended by BCO (BCO 2014). *'Occupied hours'* were defined as '08:00 to 18:00 on all weekdays including bank holidays' (10 hours x 5 days x 52.2 weeks = 2610 hours/year).

Heating and cooling were setback *outside* normal working hours, figure 20. In office areas, heating and cooling were setback from 19:00 to 07:00 on weekdays. At weekends, heating and cooling were setback from 07:00 to 19:00 and turned off outside of these hours. In common areas, the heating and cooling were on from 07:00 to 19:00 on weekdays but switched off outside of these hours. Common areas were heated to the setback level at weekends between 07:00 and 19:00 only. No cooling was provided in common areas at weekends. During load-shift periods (17:00 to 18:00 each day), the setback levels for heating and cooling were 19°*C* and 26°C in order to minimise discomfort to building users (section 6.3.8).

The working space for each occupant was set to reflect greater density in working areas than common space. CIBSE's benchmark occupant density for office areas is 12 m^2 to 16 m^2 per person '*for city centre offices and business parks respectively*' (CIBSE 2015, section 6.2). This is a mean value for the occupied area and does not distinguish working space from common areas. The BCO propose 8 to 13 m^2 of NIA per workplace (BCO 2014). The model represented buildings fitted out as both open plan and cellular. Following the suggestion of Korolija et al. (2013), open plan offices have higher occupant area than cellular, where a single room may have one or two occupants (table 28). The occupant area in office space in open plan types was 9m^2 per person (types 1 and 3 in figure 17). In cellular types 2 and 4, this was 14m^2 per person. In common areas, occupant density was reduced to 20 m^2 per person since staff activity would be transient. This gave a mean occupant area of 9.7 m^2 per person in open plan types 1 and 3, 15.3 m^2 per person in type 2 and 14.8 m^2 per person in type 4.

Table 27 Number of occupants by building zone

	Occupants in each zone				
	Office space			Common area:	People / building
Type	**Zone1a**	**Zone1b**	**Zone1c**	**Zone2**	
Type1 OD	46	-	-	3	148
Type2 CS	14	12	-	6	95
Type3 OA	46	-	-	3	149
Type4 CDO	16	7	6	3	97

Table 28 Office and common area environmental factors applied to all built form types, age bands and HVAC types

	Office space (zone 1)	**Common areas (zone 2)**	**Reference**
Heating setpoint / setback (°C)	21-23 / 16	21 / 16	CIBSE (2015) &
Cooling setpoint / setback (°C)	22-24 / 28	25 / 28	BCO (2014)
Load shift period setback: heating, cooling (°C)	19, 26	16, 28	CIBSE (2015)
Occupant area (m^2/ person)	open plan: 9 cellular: 14	20	CIBSE (2015) BCO (2014)
Fresh air rate (l/s.person)	10	10	HM Government (2010a)
Equipment power density (W/m^2)	10	0	BCO (2014), CIBSE (2012)

The ventilation rate was 10 l/s per person in accordance with the requirements for offices in The Building Regulations (HM Government 2010a). The timing and volume of the air flow were determined by the occupancy schedule (figure 19).

Commercial lighting efficiency has increased but the frequently of lighting upgrades is unknown. Newer generation lamps (such as fluorescent type T5) consume less energy for the same light output than older ones (such as T12). It was assumed that lighting in all of the modelled building cases would have been replaced at least once and that the 1990s cases would show a moderate improvement on the earlier buildings. The heat gain from lighting was determined by the illuminance level and the lighting efficiency. The target illuminance level was 400 lux in all areas, being the mean of 300 to 500 lux proposed by (CIBSE 2012 , section 9.1). The internal heat gain from lighting proposed by CIBSE and BSRIA is 12 W/m^2 (CIBSE 2012, section 9.5), (Hawkins 2011). The official guidance in England on specifying lighting to ensure compliance with the energy efficiency requirements of The Building Regulations is contained in the '*Non-domestic Building Services Compliance Guide*' (HM Government 2014). The requirements for lighting were introduced in the 2010 Edition and made more stringent in 2013 (DCLG 2006), (HM Government 2010b), (HM Government 2014). The minimum '*lighting efficacy'* for existing buildings, stated in this Guide, is summarised in table 29. 'Lighting efficacy' is the light output divided by the electricity consumption of the lamps plus control gear. The trend (of increasing efficacy), indicates the scale and direction of mandatory energy efficiency improvements over time and this was reflected in the model. The change in lighting efficacy between the 2010 and 2013 editions is 9%. A similar change was made to the lighting energy gain: 13 W/m^2 for the 1970s cases, 12 W/m^2 in the 1980s cases and 11 W/m^2 in the 1990s cases.

Table 29 Recommended minimum lighting efficacy in existing buildings

Edition	**Lighting efficacy (lumens / W)**
2006	lighting not specified
2010	55
2013	60

Source: *(DCLG 2006; HM Government 2010b; HM Government 2014)*

CIBSE's benchmark annual energy consumption for lighting in an air-conditioned standard office is 27 to 54 kWh/m^2.yr (CIBSE 2012, section 9.5). These lighting levels and heat gains were considered to be representative, irrespective of property age, reflecting lighting upgrades. A day-lighting control was implemented with three steps, which simulated blocks of lights being switched on in response to changing levels of daylight (DesignBuilder 2011, p.221).

The lighting schedule was set to provide adequate lighting during occupied hours. The office and common area lights were on from 07:00 to 19:00 on weekdays, subject to the stepped daylight reduction described above. Outside of working hours, some lighting in offices often remains on: for security reasons or because staff do not turn them off. It was assumed that lighting was reduced to 30% of full daytime power consumption, the level proposed by Jenkins & Newborough (2007).

The power consumption of IT equipment was based on benchmarks stated in the literature. BCO propose 13 to 15 W/m^2 over a floor area of at least 1000 m^2 (BCO 2014). CIBSE adopt a '*guide figure*' of 15 W/m^2 for IT power loads (CIBSE 2012, section 12.2). CIBSE's benchmark IT energy consumption for an air-conditioned standard office is 23 to 31 kWh/m^2.yr, based on IT equipment operating in 60% of the floor area for 2750 to 3250 hours per year.

In this research, the floor area with IT equipment was the office area (which excluded common areas). This was the same as the area for calculating DHW loads (table 26) and represented 77% to 87% of the total internal area. The IT power load was 10 W/m^2 in office areas reflecting the increasing popularity of laptops with lower power consumption than desktops. IT equipment was assumed to be consuming this power from 08:00 to 18:00 on weekdays. IT equipment was assumed not to be present in common areas. Outside of working hours on weekdays and at weekends, it was assumed that IT power consumption was 15% of the working hours level, to allow for equipment running for operational reasons or because the users had left it running. This is similar to 20% power consumption for non-working hours, proposed by Menezes et al. (2014).

6.3.5 Parameters of Variability

Key factors that affect heating and cooling energy consumption are treated as parameters in order to determine the potential range in electricity consumption and shiftable load for each type. Important factors are detailed below; default values from DesignBuilder are accepted for others. In the 'real world', variation in electricity consumption exists within any group of similar buildings but the simulation software (detailed in section 6.3.6) produces a deterministic output. The model output is made to represent some variation by selecting the factors that are most significant for heating and cooling electricity consumption and assigning a range of values to them.

Tian & Choudhary (2012) identified 16 parameters that affect gas and electricity use in school buildings. Although schools have different occupancy patterns and HVAC demands from offices, this work indicated factors which would affect electricity consumption in offices. Tian & Choudhary (2012) suggested that it would be '*computationally prohibitive'* to calculate the model sensitivity to each of these parameters. They chose four parameters with the greatest impact on gas and electricity use (table 30).

Tian & Choudhary (2012) believed that a higher proportion of lighting remains on at night than stated in the National Calculation Methodology (BRE 2014a). This was referred to as '*M-schedule'*. The schools were assumed to be heated by gas and not to have cooling systems. The daily and seasonal occupancy schedules differ from office buildings. Heating and cooling setpoints directly affect shiftable thermal loads. Cooling setpoint was included since many offices have cooling systems (section 3.5.3.1).

Table 30 Top four factors affecting electricity use in schools.

Gas	Electricity
Heating setpoint	M-schedule
Ventilation	Equipment in classroom
Infiltration	Daylighting
Roof-U value	Lighting in classroom

Source: *Tian & Choudhary (2012)*

The modelled buildings were all assumed to have sealed windows so ventilation was not varied. Infiltration and roof U-value were fixed by age of building. '*M-schedule' was* recognised as important by assuming that a proportion of lighting and IT remained on outside of working hours (section 6.3.4).

The setpoints for heating and cooling in office areas were considered important factors affecting energy consumption. The value ranges for heating and cooling in office area zones (table 28) were used as the parameter values. These were used in pairs in order to reduce the likelihood of simultaneous heating and cooling (table 31). The setpoints used in common areas were unchanged (table 28). Building orientation could affect electricity consumption, especially in building types 1 and 2 which were not symmetrical. The orientation of the north axis was chosen to be either 0° or 90° (table 31).

Table 31 Parameter values used in simulations: one pair of heating and cooling values was used in each simulation

Parameter	Values
Building orientation	0°, 90°
For office areas: (temperature °C) {heating setpoint | cooling setpoint}	{21|22}, {22|23}, {23|24}, {21|23}, {21|24}, {22|24}

With a single building simulation, it was noted that when the HVAC system started operation there was a large demand 'spike' due to EnergyPlus assuming that the system always had the capacity to service the load (section 6.3.6). It was assumed that the heating and cooling systems were appropriately sized by EnergyPlus. The effect of multiple buildings was expected to magnify this spike, due to the software being deterministic. However the purpose of this study was to investigate the load shifting during the day, not transient effects from HVAC operation. Initial simulations 'staggered' the HVAC start and end times but this created unnecessary complexity which made it harder to separate out the effect of the load shifting from the HVAC operation schedule.

6.3.6 Model Implementation

Four built form types were simulated in EnergyPlus. Figure 21 illustrates how the built form types (in figure 17) were represented and simulated. The building types were first entered in DesignBuilder version 3.2.0.067 (DesignBuilder n.d.). The graphical interface to this tool made it easier to enter and check the building dimensions, fabric values, HVAC design and operating schedules. Initial simulations were run to check the design and output in the BaU and load-shift cases. Since a large number of simulations were required with different parameter values, the parametric tool, jEPlus, version 1.4, was used (Zhang & Korolija 2014). Both DesignBuilder and jEPlus use EnergyPlus, (US Department of Energy 2015) to simulate the energy consumption but the user does not interface directly with EnergyPlus. The input data file (IDF) for each building was exported from DesignBuilder and edited to make it compatible with jEPlus.

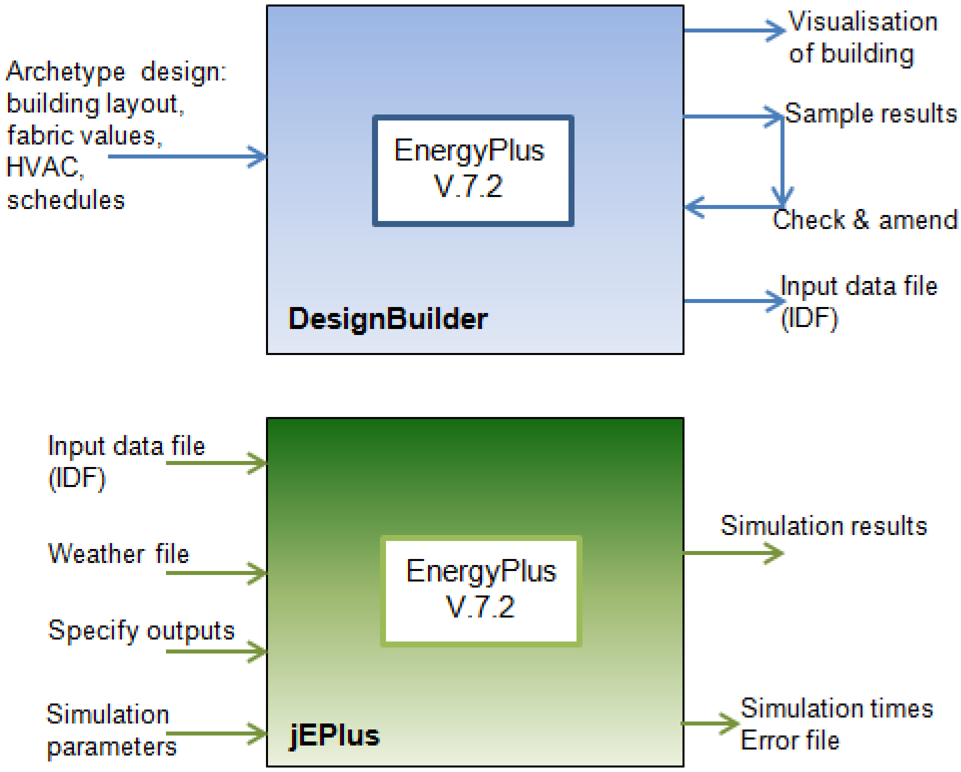
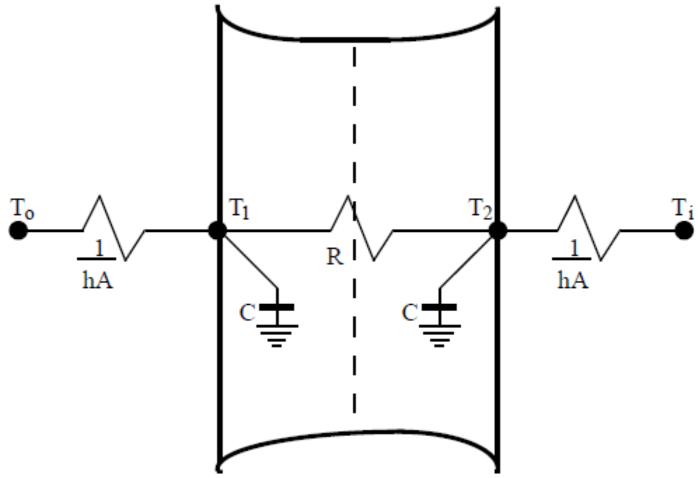


Figure 21 Overview of the software implementation of the model

In jEPlus, the parameters with a range of values (section 6.3.5, table 31) were replaced with search strings and the value ranges entered. The EnergyPlus outputs were specified (table 41) and the weather file was selected. 10-minute timesteps were used (section 6.3.10.1) and the output files were analysed using Matlab, version R2013a (Matlab n.d.).

A conduction transfer function (CTF) method is used by EnergyPlus to calculate the energy transfer through building elements (EnergyPlus 2012b, p.60). CTFs are a useful method of calculating the heat flux of a building element because the internal temperatures and fluxes are not required. A potential drawback is that CTFs become unstable as the timestep decreases, especially for buildings with high thermal mass (EnergyPlus 2012b). This is due to rounding and truncation errors and is mitigated by using more terms. This method which only calculates temperatures at the surfaces of building elements is adequate for the constructions considered but would need to be modified if phase change materials (PCM) embedded in walls were being evaluated.



Source: *EnergyPlus (2012b)*

Figure 22 Representation of a single layer slab

The representation of heat conduction through a single layer slab in EnergyPlus is based on the work of Seem (1987) (EnergyPlus 2012b). This is shown in figure 22, where

Equation 3: $R = \frac{l}{kA}$ and Equation 4: $C = \frac{\rho C_p l A}{2}$

R is the thermal resistance of the slab of thickness, *l* and area, A. *h* is the convection coefficient and k the thermal conductivity in W/mK. T_1 and T_2 are the temperatures of nodes 1 and 2 at the surface of the slab. T_o and T_i are the external and internal temperatures. C is the thermal capacitance of each node of density, ρ and specific heat capacity, C_p.

The EnergyPlus weather file format is based on the Test Meteorological Year 2 (TMY2) format (EnergyPlus 2012a, p.3). TMY2 data are derived from 30 years of observed data (Crawley 1998). In simulations carried out by Crawley, this was found to be closer to the long-term mean than other data sets. *'Simulations using the TMY2 data set more consistently match the simulation results for the... 30-year period than any other data set.'* (Crawley 1998). The EnergyPlus weather file contains the same data as in a TMY2 file but rearranged to make inspection easier (EnergyPlus 2012a). A minute field allows sub-hourly data to be entered although the weather file used in these simulations has hourly timesteps.

'Quasi-static' models were used to represent most factors in EnergyPlus (EnergyPlus 2012b, p.56). A factor such as zone temperature was calculated for the start of a timestep and then held constant for that timestep.

The HVAC systems in this research were represented using the '*Simple HVAC'* model in DesignBuilder which uses the EnergyPlus '*ZoneHVAC:IdealLoadsAirSystem*' model (DesignBuilder 2011, p.303), (EnergyPlus 2012b, p.962), (EnergyPlus 2012c, p.897). EnergyPlus sized the heating and cooling capacity for each zone using a heat balance method (EnergyPlus 2012b, p.388). In the procedure for sizing, EnergyPlus assumed that each zone was serviced by an air-conditioning unit with infinite capacity (as measured by flow-rate). Air was supplied at the constant design supply temperatures and humidity levels specified in the IDF file. In the sizing calculations the inflow air temperature, T_{in}, was fixed at the zone cooling or heating design supply air temperature (12°C or 35°C). T_z was the zone temperature. The system output, Q_{sys}, is made equal to the zone demand and the air mass flow rate, $\dot{m}_{sys}$ was calculated:

$$\dot{m}_{sys} = {Q_{sys}}/{C_{p,air}(T_{in} - T_z)}$$

Equation 5:

The gas and electricity input required for this ideal HVAC model were calculated by applying the fixed CoPs in section 6.3.3.

The effect of changing from Greenwich Mean Time (GMT) to British Summer Time (BST) for the summer period is automatically modelled in EnergyPlus (DesignBuilder 2011, p.162). One hour is added to GMT during the BST period to determine operation schedules. This has the effect of making it appear that building activity starts one hour earlier during the summer because the results were displayed in GMT.

6.3.7 Quality Assurance of Model

This section describes the steps taken to verify the performance of the model. These were:

- calculations to compare the expected values of energy consumption with output from EnergyPlus for each end use (section 6.3.7.1)
- comparison of modelled energy consumption per unit area with published benchmarks (section 6.3.7.2)
- analysis of times series plots of temperature, ventilation and heating / cooling to confirm the profiles were as expected (section 6.3.7.3).

6.3.7.1 Breakdown of Energy by End Use

This section describes the checks on the model output values to confirm that they were consistent with expectations based on the input values. The model input values for domestic hot water, lighting, IT, fans and pumps were used to manually calculate the power consumption for these uses, which were compared with the values reported by DesignBuilder.

Domestic Hot Water (DHW) heating rate

The maximum DHW heating rate (in kW) was calculated manually and compared with data calculated by EnergyPlus. The requirement for DHW was entered in DesignBuilder (DB) in litres/m^2.day (table 32, column 2). This was calculated by multiplying the DHW demand by the *occupant density* (person/m^2) for the office area. ‘Occupant density’ was entered in DB: this being the reciprocal of ‘occupant area’ stated in table 28. The DHW rate was 10 l/person.day. When calculating the maximum rate of hot water demand, DB assumed that the daily volume of hot water was supplied over eight hours. The DHW heating rate was checked with dT 50 K and Cp 4.187 kJ/kg.K, to give the values in table 32, column 5. The system efficiency, η, was 0.84 in the present day scenario (the HVAC system was used to supply DHW). The values calculated by EnergyPlus are given in table 32, right column. These were considered close enough to the manually calculated values.

Table 32 Hot water demand: calculated and from model in the *current* scenario

Built Form Type	DHW demand (l/m^2.day)	Office space (m^2)	Max DHW flow rate (l/hr)	Max DHW power (kW), *calculated*	Max DHW power (kW), *simulation*
1	1.10	1264	173.8	9.710	9.716
2	0.70	1116	97.6	6.759	6.748
3	1.11	1254	174.0	9.636	9.642
4	0.70	1254	109.7	7.596	7.583

Lighting

Table 33 Peak energy consumption from lighting: comparison of calculated and model values

		Types 1 and 2		Types 3 and 4	
Age Band	Lighting heat gain (W/m^2)	Calculated Lighting heat gain (kW)	EnergyPlus Lighting heat gain (kW)	Calculated Lighting heat gain (kW)	EnergyPlus Lighting heat gain (kW)
1970s	13	19.76	19.76	18.73	18.73
1980s	12	17.43	17.43	17.29	17.29
1990s	11	15.98	15.98	15.85	15.85

The maximum heat gain from lighting for each building case was calculated manually and compared with data generated by EnergyPlus. The illuminated floor areas for type 1 and 2 buildings were 1453 m^2 and for types 3 and 4, 1441 m^2 (table 21). The lighting heat gain in 1970s, 1980s and 1990s buildings was 13, 12 and 11 W/m^2 respectively (section 6.3.4). Table 33 compares the maximum values of heat gain from manual calculations with data generated by EnergyPlus.

IT

IT power was the product of the office floor area and the IT equipment density, with a reduction to 15% of daytime level from 18:00 to 08:00 (section 6.3.4). The IT equipment density was 10 W/m^2 in office areas and zero in common areas. This was used to manually check the expected IT power at full occupancy against values from the simulations (table

34). The comparison of simulated and calculated values were considered to be sufficiently close.

Table 34 Comparison of maximum IT power from manual calculations and simulations

Built Form Type	**Office space (m^2)**	***Calculated* IT power (kW)**	**IT power from *simulation* (kW)**
1	1264	12.64	12.64
2	1116	11.16	11.16
3	1254	12.54	12.54
4	1254	12.54	12.54

Auxiliary energy

Auxiliary energy is the sum of fan and pump energy. Fan energy was calculated from the fresh air rate (number of occupants in the building multiplied by the fresh air rate per person). This was multiplied by the specific fan power and the occupancy fraction (sections 6.3.3.3 and 0). The number of occupants in each building at full occupancy was calculated in table 27. This is reproduced in table 35 with the fan power for 1980s buildings with gas heating. The fresh air rate was 10 l/person for all building cases and SFP was 1.1 W/l.s.

Table 35 Comparison of calculated and simulated fan power at full occupancy, 1980s cases

Built Form Type	**Occupants / building**	**Building fresh air (l/s)**	**Calculated fan power (kW)**	**Simulated fan power (kW)**
1	148	1484.5	1.633	1.633
2	95	949.5	1.044	1.044
3	149	1485.3	1.634	1.620
4	97	971.1	1.068	1.068

The pump power was the product of the heated floor area and the pump power density. The pumps operated according to the heating schedule. The pump power density was 0.9 W/m^2

for all cases (section 6.3.3.3). Manually calculated values for full occupancy were compared with values calculated by EnergyPlus in table 36. These values apply to all age bands in the model and both gas and electric heating.

Table 36 Comparison of calculated and simulated values of HVAC pump power applying to all simulated age bands

Built Form Type	**Heated area (m^2)**	***Calculated* maximum pump power (kW)**	***Simulated* maximum pump power (kW)**
1	1453	1.307	1.307
2	1453	1.307	1.307
3	1441	1.297	1.297
4	1441	1.297	1.297

Ventilation

The mechanical ventilation rate, A_v, was calculated for each built form type and compared with data from the simulations. This was calculated using equation 6.

$$A_v = \frac{a_r.n.f.60.60}{V_b.1000}$$ (ac/h) Equation 6

a_r is the fresh air rate in l/s.person, *n* is the number of occupants in the building and V_b the building internal volume (m^3). The occupancy fraction, f, has values between 0 and 1 (full occupancy). The factors of 1000 and 3600 convert from litres per second to air changes per hour. The fresh air rate, a_r, was 10 l/s.person in all cases. Values of occupant number, p, were taken from table 27. The floor to ceiling height used to calculate V_b was 3.207m.

The total ventilation rate was reported for the whole building by DesignBuilder. This was the sum of mechanical ventilation and infiltration. For the 1990s buildings, infiltration was set to 0.3 ac/h. This was added to the mechanical ventilation rate to obtain the total air flow rate. The mechanical ventilation rates at full occupancy from EnergyPlus and from manual calculations are given in table 37. These were considered sufficiently close.

Table 37 Calculation of ventilation rates at full occupancy for 1990s building

Built Form Type	Internal volume (m^3)	Calculated mechanical ventilation rate (ac/h)	*Simulated* mechanical ventilation rate, 1990s case (ac/h)
1	4658.6	1.147	1.184
2	4658.6	0.734	0.71
3	4620.2	1.157	1.175
4	4620.2	0.757	0.722

6.3.7.2 Comparison of Energy Consumption with Reference Sources

The annual energy consumption for each model case in the 'business as usual' (BaU) scenario was compared with published benchmarks. The total annual energy consumption and the consumption by separate end uses were compared with reference sources.

The total energy consumption per unit area was compared with data from the *'Analysis of Display Energy Certificates for Public Buildings, 2008 to 2012'*, (Hong & Steadman 2013). The building areas used in the comparison were 'gross internal area' (GIA) consistent with the measurement convention for DECs for offices in CIBSE TM46 (Field et al. 2008). The floor areas were 1452.6 m^2 for types 1 and 2 and 1440.7 m^2 for types 3 and 4 (table 21 in section 6.3.1). The heating and cooling setpoints in office areas were set to the mid values of 22°C and 23°C respectively to represent the mean scenarios (table 28).

Figure 23 compares the modelled energy consumption for the cases with gas heating in the BaU scenario with median values from the analysis of DECs for offices (Hong & Steadman 2013). Cases 4, 10, 16 and 22 represent 1980s construction and have similar gas and electricity consumption to the data from DECs. The 1970s cases (2, 8, 14 and 20) have 35 to 38% higher energy consumption while the 1990s cases (6, 12, 18 and 24) have 30% lower energy consumption. These simulations relate to buildings with electric cooling and mechanical ventilation, whereas the benchmark data are based on a mix of buildings, including some with natural ventilation. Buildings with mechanical ventilation and cooling had higher energy consumption in Hong & Steadman (2013). Cases 8 and 14 are open plan types with 1970s fabric. They consumed slightly more energy overall than the cellular types 2 and 20 with the same fabric.

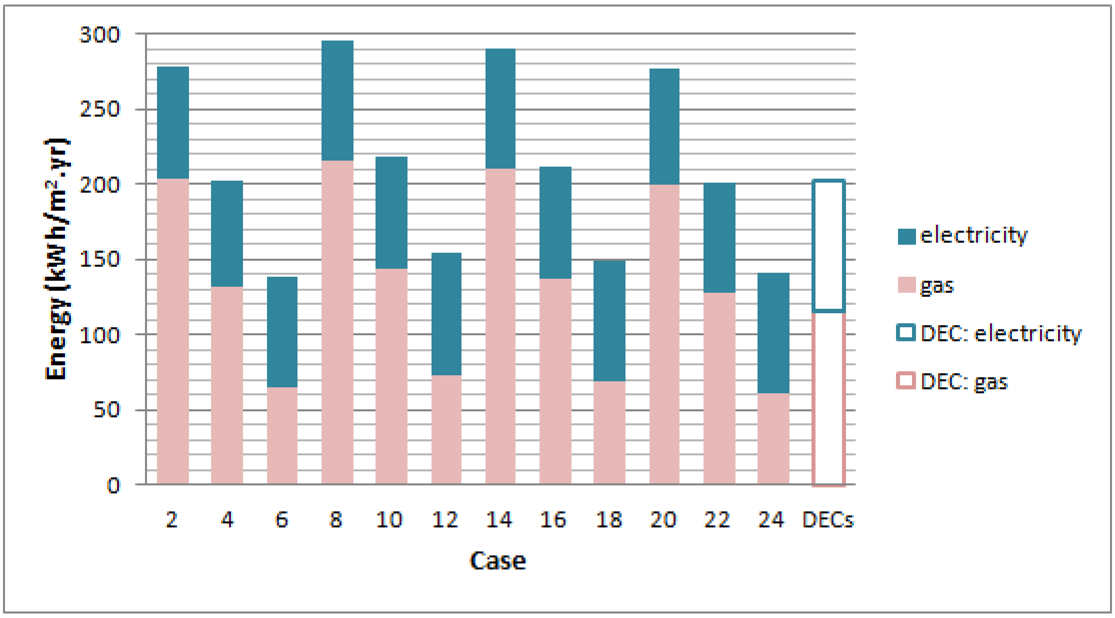


Figure 23 Energy consumption for gas heated model cases in the BaU scenario compared with benchmark data from DECs. Source: *Hong & Steadman (2013)*

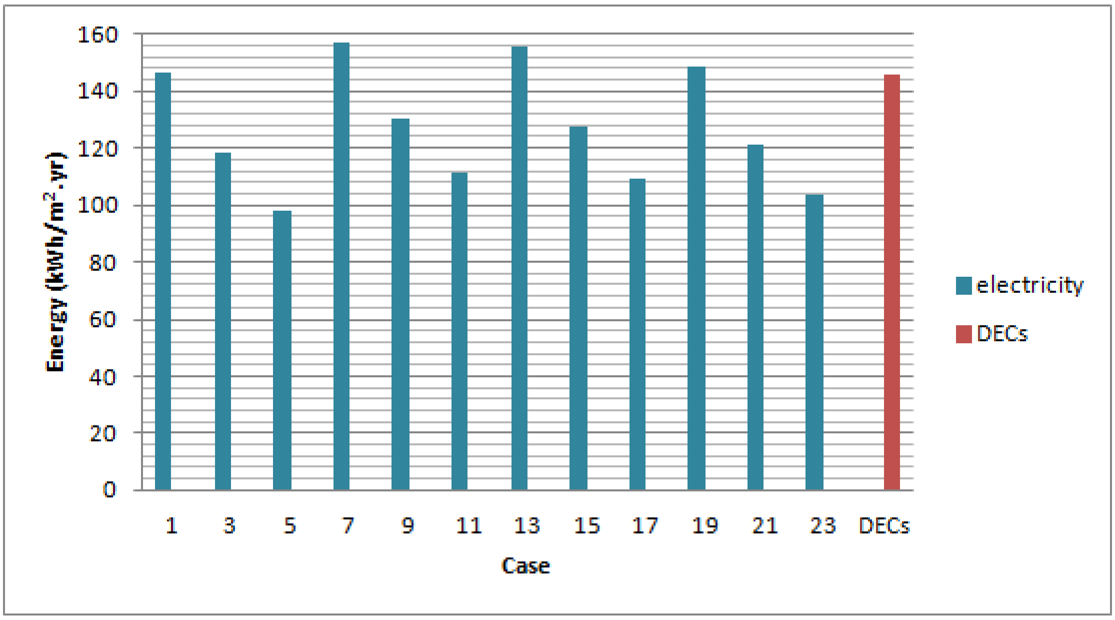


Figure 24 Energy consumption for model cases with electric heating in the BaU scenario compared with benchmark data from DECs. Source: *Hong & Steadman (2013)*

In the electric heating scenario, the CoPs of both space heating and cooling were increased from the gas heated cases (table 24 compared with table 23). The energy consumption of lighting and IT were unchanged. The effect of this was to reduce the overall energy consumption and reduce the proportion due to heating and cooling. Figure 24 compares model cases in the electric heating scenario with data from Hong & Steadman (2013). Cases 3, 9, 15 and 21 represent buildings with 1980s construction. These consumed between 33% less energy than the benchmark (case 5) and 8% more (case 7), which was expected since the heating and cooling CoPs were higher.

The annual energy consumption data from the model developed in this research were compared with data from Energy Consumption in the UK (ECUK) because this source disaggregates energy for ‘commercial offices’ by end use (DECC 2014c). Firstly the absolute values for ECUK are presented and then the proportions for each end use.

ECUK data are presented in ‘TWh/yr’ for the UK including Scotland and Northern Ireland. However floor area data are only available for England and Wales; no equivalent exists for Scotland or Northern Ireland (VOA 2012a). The floor area of offices in the UK is needed to derive energy per unit area data from ECUK to compare with model data. ECUK is an output from the model N-DEEM. When N-DEEM was developed, the floor space data for England and Wales ‘*were extrapolated to cover Scotland and Northern Ireland by multiplying by the ratio of United Kingdom population to that of England and Wales’* (Pout 2000). This process was applied here.

The floor area of offices in England and Wales was 92,720 thousand m^2 in 2012 (VOA 2012a). The ratio of population in the UK to England and Wales in 2014 was 1.125 (Office for National Statistics 2015). The extrapolated floor area of offices for the UK: 104,329 thousand m^2. The total energy for offices in UK in 2012 (21.26 TWh) (DECC 2014c) was divided by the total area to give 203.8 $kWh/m^2.yr$, mean energy. These data are presented alongside the model data in table 38.

Table 38 Comparison of modelled energy consumption by end use with ECUK data. Data are in kWh/m^2.yr Source: *DECC (2014c)*

	ECUK	Type	Model cases with gas heating											
			2	**2**	**2**	**1**	**1**	**1**	**3**	**3**	**3**	**4**	**4**	**4**
	kWh/m^2.yr	**Age**	**1970**	**1980**	**1990**	**1970**	**1980**	**1990**	**1970**	**1980**	**1990**	**1970**	**1980**	**1990**
heating	119.4		191.26	120.19	52.60	198.79	126.63	56.00	192.76	119.16	51.89	185.66	113.41	47.93
cooling	18.8		12.21	10.34	18.24	13.00	10.92	19.22	12.03	10.07	17.79	12.04	10.10	17.98
DHW	13.2		12.07	12.07	12.07	17.38	17.38	17.38	17.39	17.39	17.39	13.68	13.68	13.68
lighting	28.4		29.57	26.09	22.00	27.83	25.69	23.57	28.56	26.36	24.19	28.31	26.13	24.01
IT	13.1		27.14	27.14	27.14	30.73	30.73	30.73	30.75	30.75	30.75	30.75	30.75	30.75
Other	10.9		6.79	6.30	6.22	8.31	7.53	7.38	8.31	7.53	7.40	7.05	6.52	6.45
Total	**203.8**		**279.04**	**202.13**	**138.26**	**296.04**	**218.88**	**154.28**	**289.80**	**211.27**	**149.41**	**277.48**	**200.58**	**140.79**
	ECUK	**Type**	**Model cases with electric heating**											
			2	**2**	**2**	**1**	**1**	**1**	**3**	**3**	**3**	**4**	**4**	**4**
	kWh/m^2.yr	**Age**	**1970**	**1980**	**1990**	**1970**	**1980**	**1990**	**1970**	**1980**	**1990**	**1970**	**1980**	**1990**
heating	119.4		64.42	40.40	17.67	67.04	42.58	18.82	65.01	40.07	17.43	62.54	38.13	16.10
cooling	18.8		8.54	8.07	14.54	9.07	8.52	15.32	8.39	7.86	14.18	8.42	7.88	14.33
DHW	13.2		10.56	10.56	10.56	15.21	15.21	15.21	15.22	15.22	15.22	11.97	11.97	11.97
lighting	28.4		29.57	26.09	22.00	27.83	25.69	23.57	28.56	26.36	24.19	28.31	26.13	24.01
IT	13.1		27.14	27.14	27.14	30.73	30.73	30.73	30.75	30.75	30.75	30.75	30.75	30.75
Other	10.9		6.21	6.22	6.22	7.39	7.39	7.38	7.39	7.40	7.40	6.44	6.43	6.45
Total	**203.8**		**146.44**	**118.48**	**98.12**	**157.26**	**130.12**	**111.02**	**155.31**	**127.65**	**109.17**	**148.43**	**121.29**	**103.60**

In table 38, the energy consumed by HVAC fans and pumps was matched to 'other' in the ECUK data. With the 1980s gas heated cases, the total energy consumption is similar to ECUK data. Heating energy is greater with the 1970s cases and lower in the 1990s cases. The cooling energy consumption in ECUK is similar to the 1990s buildings. With the electric heated cases, heating and cooling consumption is lower across all age bands due to the higher CoPs with ASHPs. This has the effect of reducing the amount of energy available for load shifting. IT power consumption in all model cases was at least twice that expected from ECUK but it was within the range suggested by CIBSE of 23 to 31 KWh/m^2.yr (CIBSE 2012), section 6.3.4.

The proportions of energy for each end use from the simulations were compared with the total energy from all fuels (such as electricity, gas and oil) in ECUK (DECC 2014c). The 'other' category includes catering and miscellaneous end uses which were not represented in the simulations. Figure 25 disaggregates the modelled energy consumption (presented in figure 23) and compares it with ECUK. This is for gas heated cases in the BaU scenario. The proportions of energy used for heating overall from ECUK were expected to be similar to the 1980s cases (4, 10, 16 and 22). As expected, the heating demand in the 1970s buildings is higher and the demand is lower in the 1990s buildings. The proportion of energy used for cooling is greatest in the 1990s buildings.

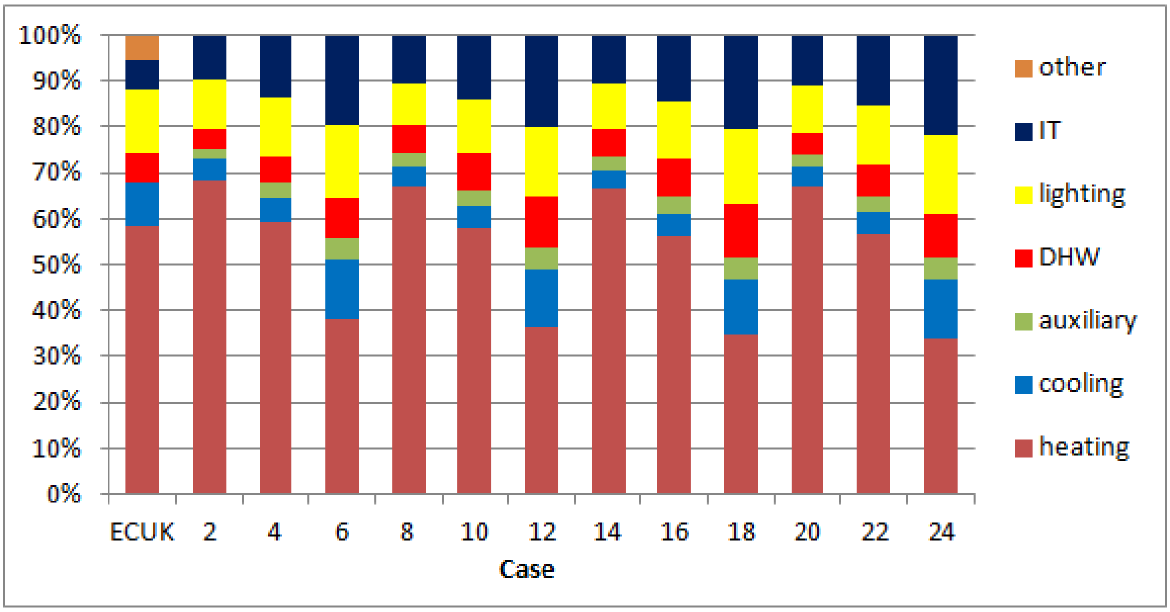


Figure 25 Energy consumption by end use: comparison of model cases with gas heating in the BaU scenario with ECUK data for 2012. Source: *DECC (2014c)*

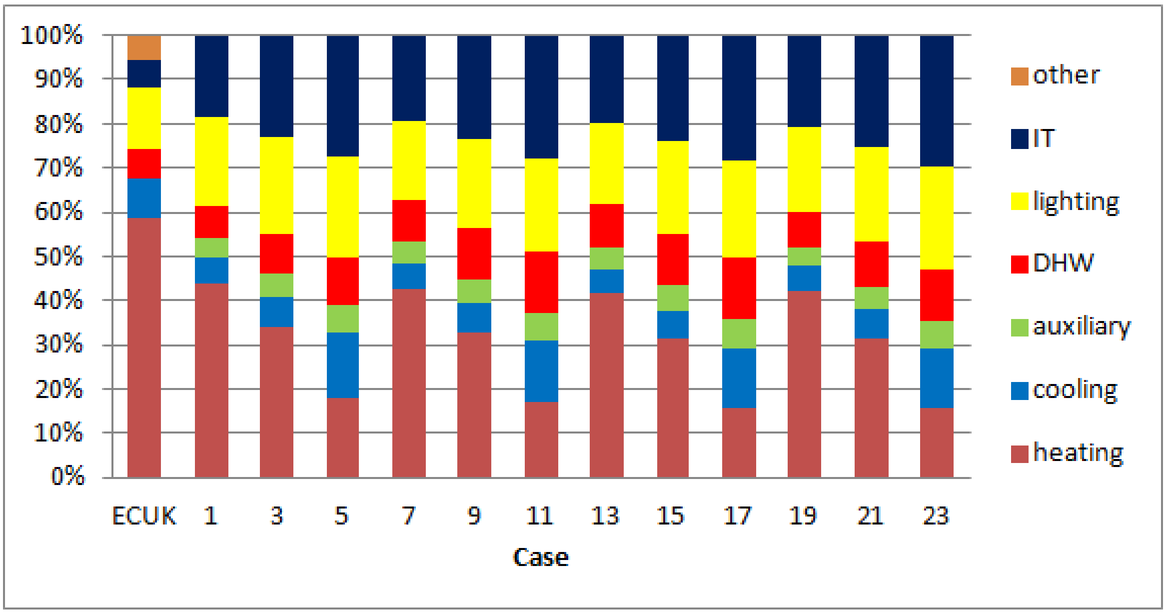


Figure 26 Energy consumption by end use: comparison of model cases with electric heating in the BaU scenario with ECUK data for 2012. Source: *DECC (2014c)*

Figure 26 breaks down the modelled energy consumption (presented in figure 24) and compares it with ECUK. This is for electrically heated cases in the BaU scenario. The proportions of energy used for heating overall from ECUK were expected to be similar to the 1980s cases (3, 9, 15 and 21). As expected, the heating demand in the 1970s buildings is higher and lower in the 1990s buildings. The proportion of energy used for cooling is greatest in the 1990s buildings. The proportion of energy for lighting and IT is higher than with the gas heating cases although the absolute values are unchanged. This is because the heating and cooling efficiencies were increased but other parameters were unchanged.

6.3.7.3 Time Series Analysis of Model Data

A selection of dynamic, temporal plots were compared with expectations based on the input data. The internal temperatures and heating and cooling loads over a full year were examined in DesignBuilder. Figure 27 illustrates how the mean internal temperature and heating and cooling demand of one model case varied over a year in response to the outside temperature. The example is a type 3 building with 1990s fabric and gas heating in the business as usual (BaU) scenario. The heating and cooling setpoints were 22°C and 23°C respectively.

For the *occupied hours*, the mean internal temperature was held close to 22°C or 23°C (reduced or increased by the temperatures of the common areas). During the heating season, the temperature regularly dropped below 22°C. This was on weekday evenings or at weekends. On weekdays from 19:00 to 07:00, the heating was setback to 16°C; at weekends from 19:00 to 07:00, it was turned off (section 6.3.4). During warm weather, the internal temperature frequently exceeded 23°C. This was on weekdays after 19:00, or at weekends. On weekdays from 19:00 to 07:00, cooling was setback to 28°C (section 6.3.4). At weekends, cooling was setback to 28°C in office areas from 07:00 to 19:00 and turned off outside these hours. There was no cooling in common areas at weekends. Figure 27 shows the mean temperature across office and common areas. The cooling setpoint in common areas was 25°C (table 28) which increased the mean value above 23°C during some occupied hours.

The internal building temperatures were compared with setpoints and setback levels for the summer and winter. The risk of over-heating was greatest during the summer in a building with low heat loss, which in this research, was a well insulated, deep plan building. This was illustrated by a type 4, cellular building with 1990s fabric and with the highest cooling setpoint (24°C) (table 28 in section 6.3.4). This was simulated from 1st June to 31st August with gas heating (current scenario). This is illustrated in figure 28 to figure 31.

The internal temperature was most likely to be too low during the winter in a building with high heat loss. This was illustrated by considering a narrow plan building with poor insulation. A type 2 building with 1970s fabric was simulated from 1st December to 28th February. The heating was supplied by a gas boiler (current scenario) and the heating setpoint was the minimum level (21°C). These simulations were done in the BaU scenario, with no load-shifting. This is illustrated in figure 32 to figure 35.

The period that included the lowest or highest external temperatures was analysed. The temperatures of one office zone on each floor were compared with the mean internal temperature in order to indicate the relationship between the temperatures of individual zones and the building mean.

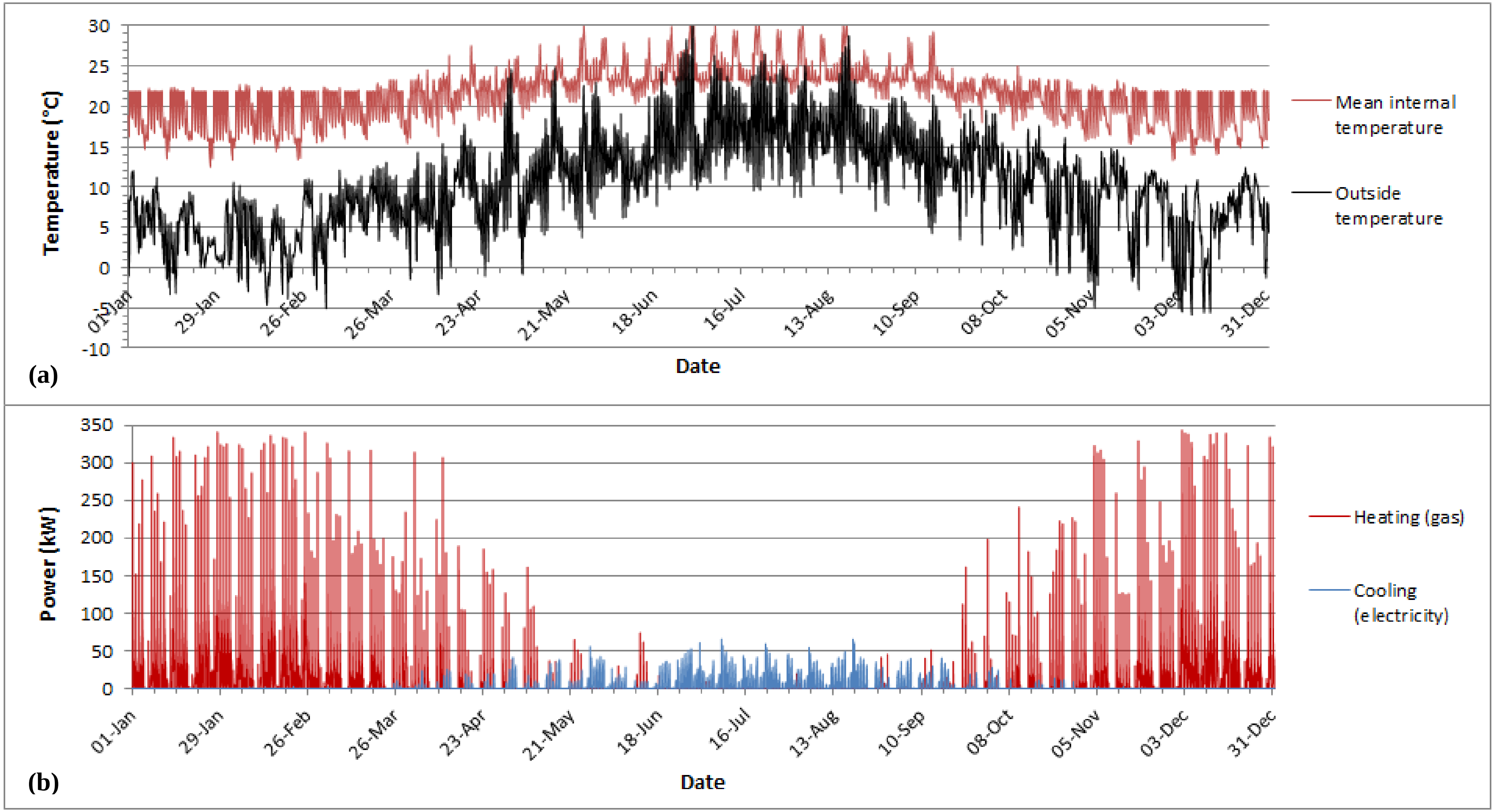


Figure 27 (a) Mean internal and external temperatures and (b) heating and cooling loads for a type 3 1990 building with gas heating (case 18) in the BaU scenario

The summer temperatures in a type 4, deep plan cellular building, with 1990s fabric in the business as usual scenario (BaU) are illustrated in figure 28. This compares the temperatures in one office area (zone 1a) on each floor, with the mean temperature (red line) and the external temperature (black line). The mean temperature closely follows the office temperatures on each floor. During *occupied hours* (08:00 to 18:00 on weekdays), the mean temperature does not exceed 24°C or fall below 21°C. The mean temperature is occasionally higher due to this being permitted in the non-working spaces (common areas). When the mean temperature exceeds 24°C, this is during the setback periods (at night and at weekends), figure 30.

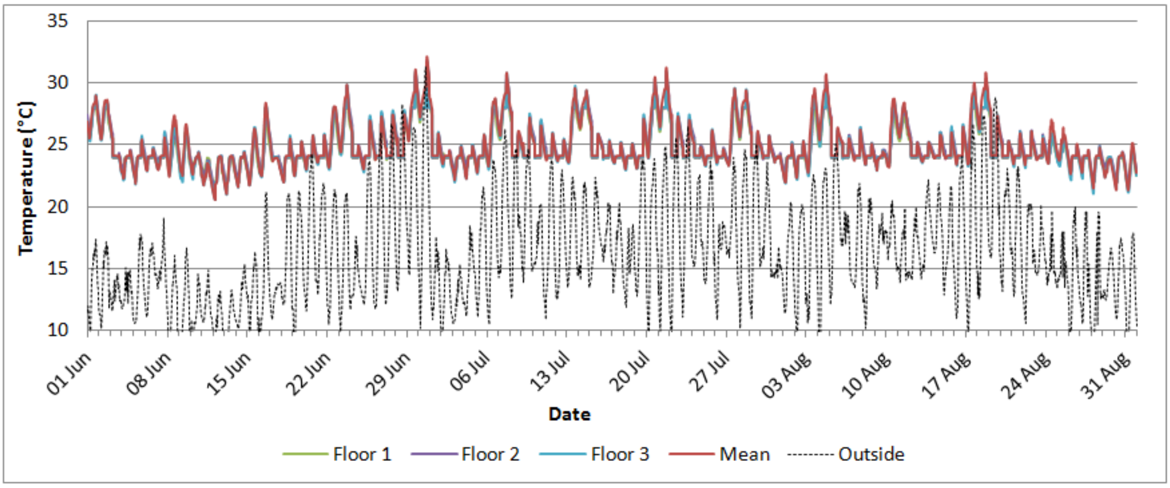


Figure 28 Summer internal temperatures for a type 4, 1990s building with gas heating in the BaU scenario. The temperature of one office area on each floor (zone 1a) is shown with the mean and the outside temperature.

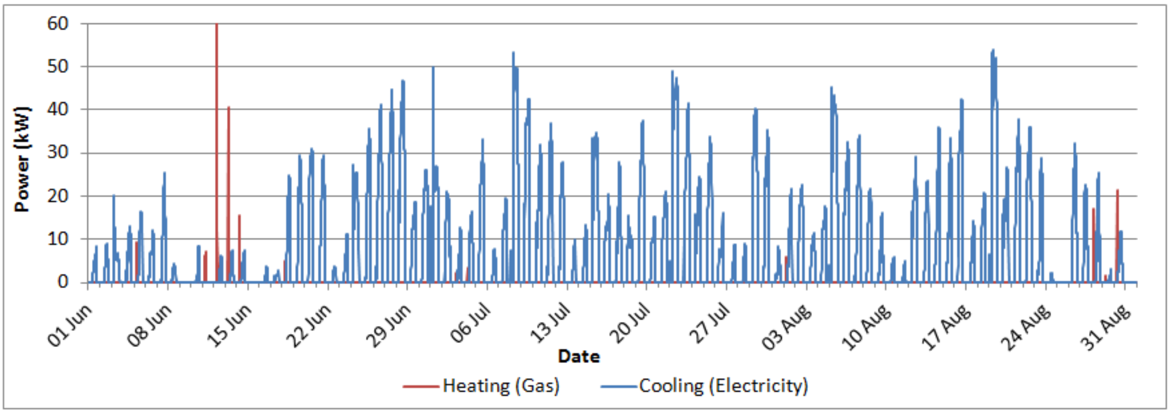


Figure 29 Summer heating and cooling demand for a type 4, 1990s building with gas heating

The heating and cooling for the same period is illustrated in figure 29. As expected, the summer thermal load is dominated by cooling which is driven by the outside temperature.

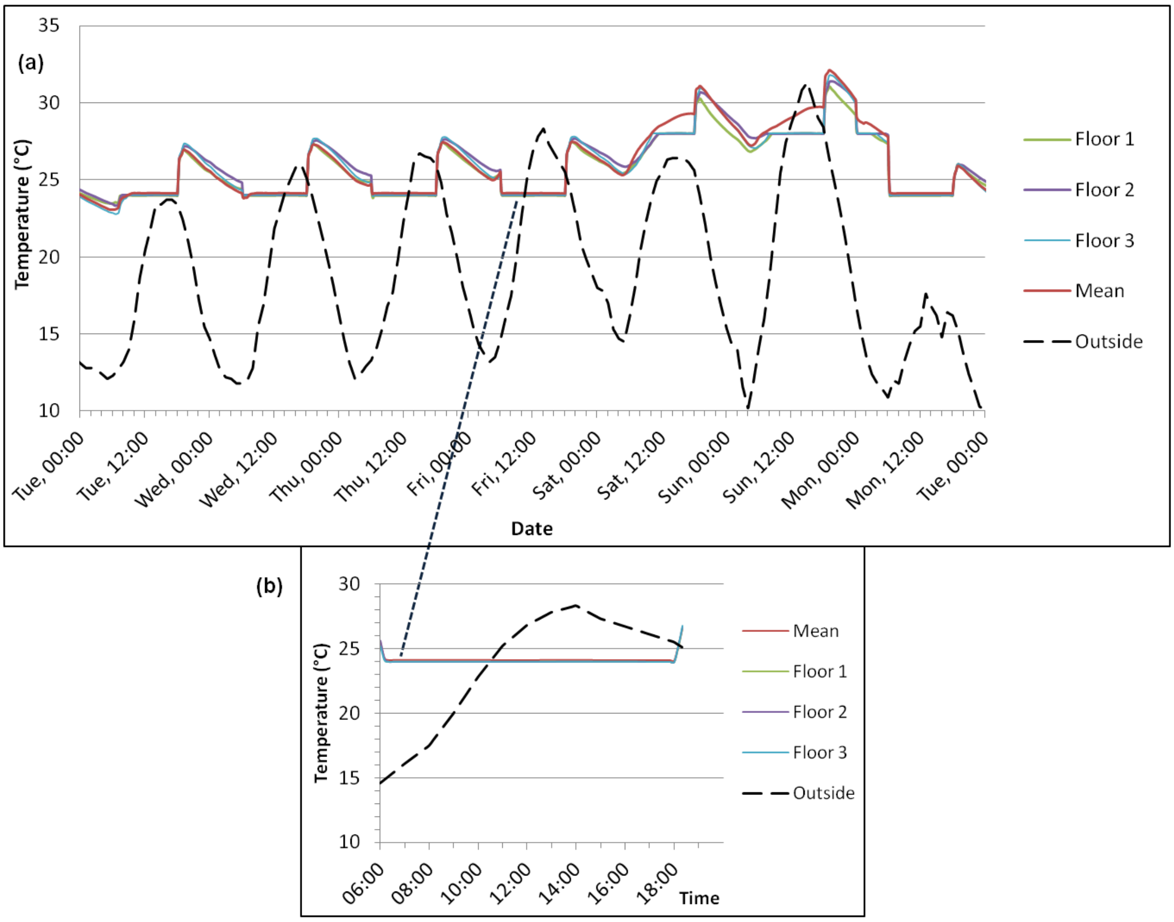


Figure 30 Internal temperatures for a type 4, 1990s building with gas heating in the BaU scenario. (a) For 25th June to 1st July; (b) for Friday 28th June

Figure 30(a) shows the temperatures in the same type 4 1990s building for one week at the end of June. The temperatures in one office area on each floor (zone 1a) were plotted alongside the building mean (in red) and the outside temperature (in black). The times given by the model output appear to be one hour earlier than actual time because the results are displayed in GMT, as noted in section 6.3.6. During working hours, the internal temperature in each zone remains at 24°C, the cooling setpoint. The temperature was allowed to rise to 28°C, the setback threshold, between 19:00 and 07:00 on weekdays and between 07:00 and 19:00 on Saturdays and Sundays. This is seen by the flat line at 28°C on the Saturday and Sunday. From 19:00 to 07:00 at weekends, no control was imposed on the temperature, which is consistent with the peaks, above 30°C on these days. Figure 30(b) shows the internal office temperatures during the occupied hours of one day when the outside temperature exceeded 25°C. Between 06:00 and 18:00 GMT (07:00 to 19:00 BST), the office temperature remains at 24°C.

The building ventilation consisted of infiltration and mechanical ventilation. The infiltration was set to a constant level of 0.3 ac/h in this case. The mechanical ventilation was set to vary according to the number of occupants in the building. Figure 31 illustrates the combined ventilation, for the same week as shown in figure 29. When the building was unoccupied, such as at night, the ventilation was 0.3 as/h, due to infiltration only. At other times, the ventilation varied in response to the occupancy fraction as expected.

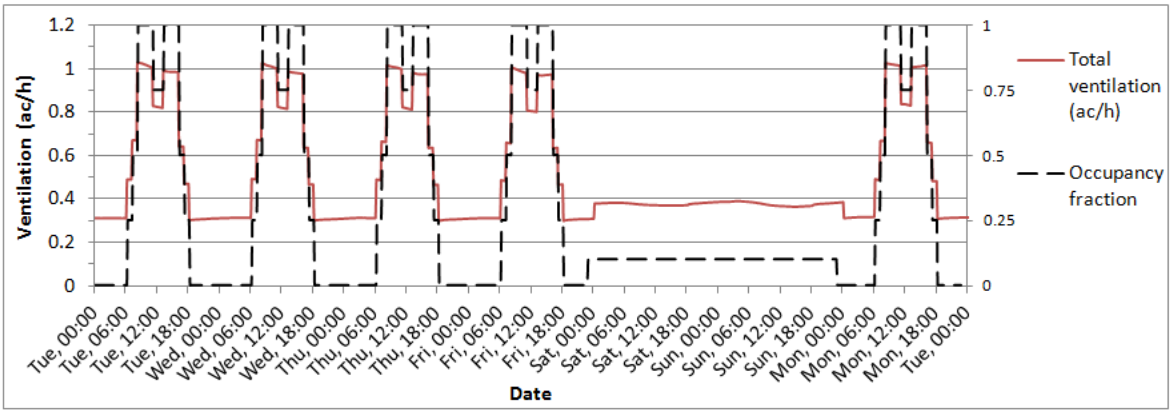


Figure 31 Total ventilation for a type 4, 1990s building with gas heating in the BaU scenario from 25th June to 1st July

The winter temperatures in a type 2, narrow plan cellular building, with gas heating and '1970s fabric' are illustrated in figure 32. The mean temperature (in red) was plotted alongside the temperature of one office area (zone 1a) on each floor and the external temperature. The temperatures in each office space were close to each other and to the mean apart from evenings and weekends, when the temperatures in the common areas had was allowed to fall lower. When the internal temperature fell below 16°C, this was during weekend nights when occupancy was low (0). This is illustrated for a single week in figure 33. The temperature remains at the setpoint level (21°C) during working hours and at the setback level (16°C) on weekday evenings and weekend daytime as specified in the model. Outside of these times, the temperature drops below this, especially on floor 3, which has an external roof. On weekday nights, the mean temperature (in red) is sometimes lower than the temperatures of individual working zones. This is because the non-working (common) areas were unheated at night (figure 20).

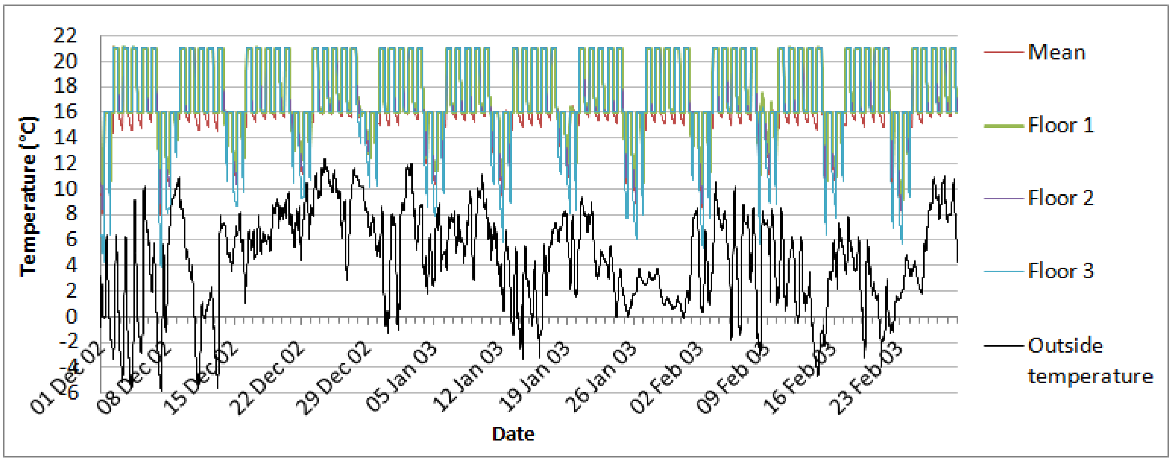


Figure 32 Winter internal temperatures in a type 2, 1970s building with gas heating in the BaU scenario

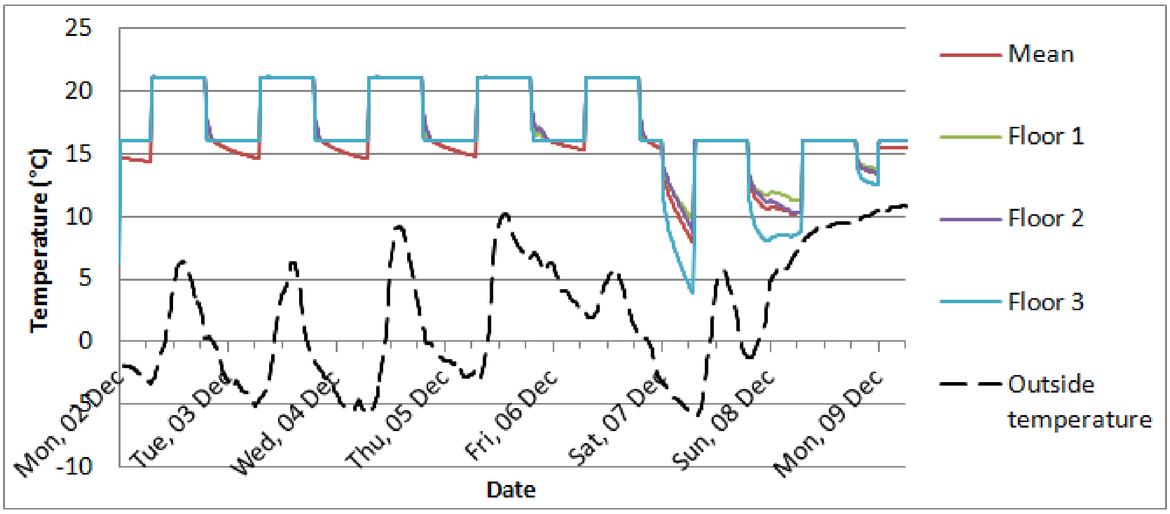


Figure 33 Internal temperatures for a type 2, 1970s building in the BaU scenario from 2nd to 8th December. The temperature of one office area (zone 1a) on each floor is shown.

Figure 34 shows the energy consumed by DHW production and for HVAC fans and pumps for the above type 2 1970s building, for the same week in December. Modelled hot water demand and fan operation were scheduled according to occupancy fraction. As expected the energy demand for these services reflects the proportion of occupants in the building. This confirms the peak DHW power of 6.75 kW for a type 2 building, stated in table 32. The peak pump power for all type 2 model cases was calculated to be 1.31 kW in table 36; this is confirmed by figure 34. The peak fan power was calculated to be 1.33 kW (table 35), which is confirmed by figure 34.

The lighting power consumption and solar gain are shown for the same week in December in figure 35. The electric lighting was set to reduce in a step-wise manner in response to increases in natural light. This behaviour is confirmed in figure 35 as the lighting energy reduces as the solar gain increases. The peak lighting electrical demand was calculated to be 19.8 kW for a type 2, 1970s building (table 33); this is confirmed by figure 35.

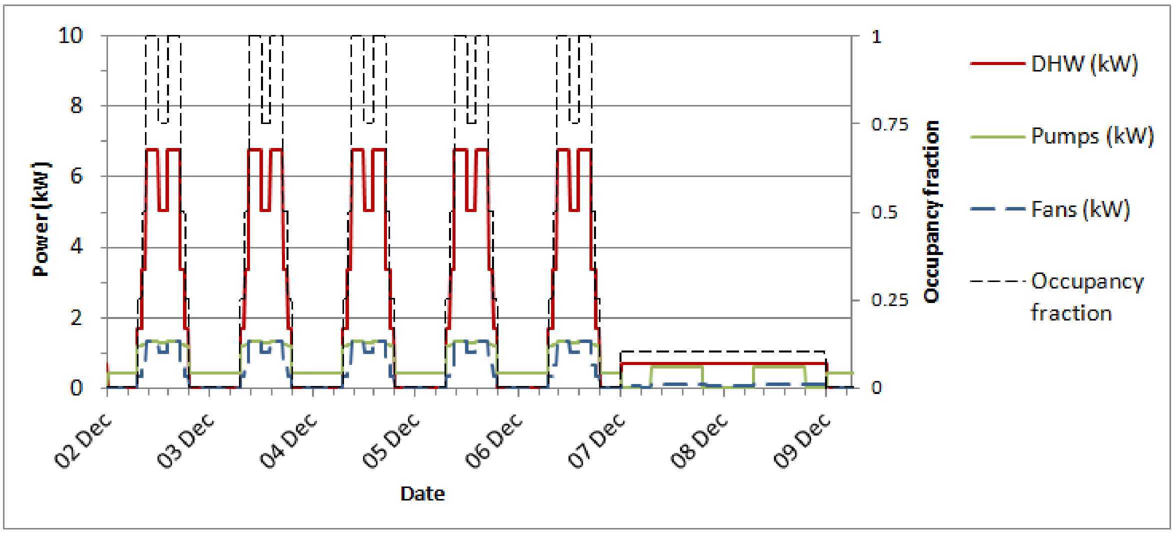


Figure 34 Energy consumed for hot water production and HVAC fans and pumps, alongside occupancy fraction for a type 2, 1970s building from 2nd to 8th December

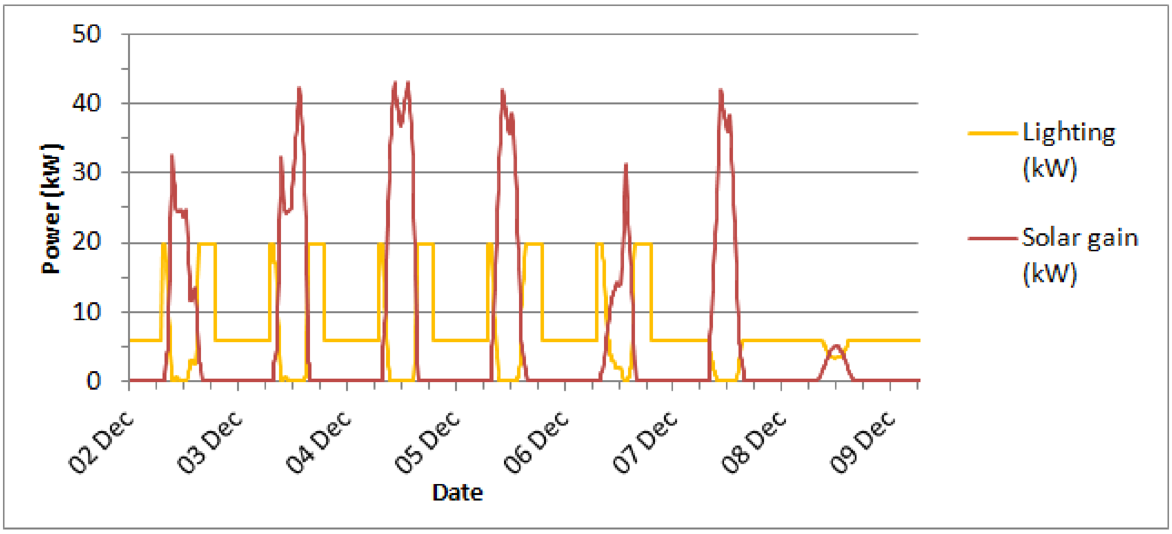


Figure 35 Artificial lighting and solar gain for a type 2, 1970s building from 2nd to 8th December

6.3.8 Simulation Scenarios and Calculations

The load shift scenario was based on the System Operator STOR service and on DNO trials of DSM services. In this research, the load shift period was one hour. This compares with the median duration of National Grid's STOR events which were just over one hour during 2012/13 (section 4.4.1). The DSM events in Western Power Distribution's Project Falcon Trial lasted between one and two hours during winter 2013/14 (section 4.4.3).

In this thesis, the load shift period was 17:00 to 18:00 each weekday. This coincided with a high demand period, exemplified by the following:

- within the 'red' bands for most DNOs (section 4.2.1)
- within a NG STOR availability window for five of the six 2014/15 *seasons*, including season 5 (27th October to 2nd February 2015) (section 4.4.1)
- covers 90% of 'triad' occurrences between 1990/1 and 2013/4 (section 4.2.1).

The number of load shifting events each year that an individual business participates in depends on their willingness and the requirements of the contract with the DNO or System Operator. If the company tendering the DSM service is concerned about loss of electricity, they may tender a high price and be called upon only rarely (as may be the case with STOR, section 4.4.1). The number of DSM events per year was suggested as 40 to 50 for STOR (section 4.4.1), compared with 40 hours of DSM for the Project Falcon Trial (section 4.4.3). In this research, DSM was simulated each weekday in order to indicate how much the shiftable load would vary within each season in response to variation in the external temperature. The analysis of shiftable load indicates the variation in load reduction from a single DSM event. This is different for each season, as will be seen in chapter 7. The effect of load shift on one day is assumed by the model to be independent of the effect on previous and successive days. The model implements a change in temperature setpoint immediately, with no allowance for a 'ramp down' as with some DSM services.

The temperature variation regarded as acceptable to building occupants for up to one hour was estimated from data published by CIBSE. According to CIBSE Guide A, '*the temperature during occupied hours in any day should not vary much from the current group-optimum temperature*' (CIBSE 2015). A change of ±2°C '*would be likely to attract attention*' but 75% of occupants would continue to be comfortable. With a temperature change of more than ±3°C, the proportion in comfort would fall below 50%, which would be undesirable. In this research, the temperature variation during occupied hours occurred during load shift periods lasting one hour, after which heating and cooling were returned to the ‘normal’ setpoints. During these periods, heating was setback to 19°C, compared with 21°C to 23°C normally. Cooling was setback to 26°C, from 22°C to 24°C. In non-working (common) areas, these thresholds were 16°C and 28°C.

Table 39 Building cases modelled

Case	**Model:** geometric type, age band, HVAC
1	Type 2 CS, 1970, heat pump
2	Type 2 CS, 1970, gas heat / electric cool
3	Type 2 CS, 1980, heat pump
4	Type 2 CS, 1980, gas heat / electric cool
5	Type 2 CS, 1990, heat pump
6	Type 2 CS, 1990, gas heat / electric cool
7	Type 1 OD, 1970, heat pump
8	Type 1 OD, 1970, gas heat / electric cool
9	Type 1 OD, 1980, heat pump
10	Type 1 OD, 1980, gas heat / electric cool
11	Type 1 OD, 1990, heat pump
12	Type 1 OD, 1990, gas heat / electric cool
13	Type 3 OA, 1970, heat pump
14	Type 3 OA, 1970, gas heat / electric cool
15	Type 3 OA, 1980, heat pump
16	Type 3 OA, 1980, gas heat / electric cool
17	Type 3 OA, 1990, heat pump
18	Type 3 OA, 1990, gas heat / electric cool
19	Type 4 CDO, 1970, heat pump
20	Type 4 CDO, 1970, gas heat / electric cool
21	Type 4 CDO, 1980, heat pump
22	Type 4 CDO, 1980, gas heat / electric cool
23	Type 4 CDO, 1990, heat pump
24	Type 4 CDO, 1990 gas heat / electric cool

The building cases, listed in table 39, were simulated for one year in the BaU case and again in the load-shift case. Parameter values (for heating and cooling setpoint and building orientation) were randomly selected from the ranges in table 31. Latin Hypercube Sampling (LHS) was used to select the values since this is implemented in the parametric simulation tool used. In the single building investigation, each simulation was carried out ten times to indicate the variation in load shift while reducing the computational demand.

The sensitivity testing on the number of simulations is reported in section 6.3.10.2. The output from each annual simulation was divided into six periods, matching the seasons for STOR 'year 8' (section 4.4.1). 'Year 8' is the period from 1st April 2014 to 1st April 2015 (National Grid 2014c). The dates of the seasons in other years may not be the same.

Only weekdays were analysed since the model assumes that at weekends, the buildings have low occupancy and the HVAC is setback (section 6.3.4). Bank holidays and holiday periods were treated as weekdays. The STOR seasons for 2014/15 vary from 20 to 80 weekdays, table 40. Although each NG Season begins at 05:00, this analysis assumes the change is at midnight.

Table 40 National Grid STOR Seasons for 2014-15 ('Year 8')

Season	Dates	Weekdays
1	1st April to 28th April 2014	20
2	28th April to 18th August 2014	80
3	18th August to 22nd September 2014	25
4	22nd September to 27th October 2014	25
5	27th October to 2nd February 2015	68
6	2nd February to 1st April 2015	40

Source: *National Grid (2014d)*

Each EnergyPlus simulation generated an *eplusout.csv* file which was analysed using Matlab, following the process in figure 36. In the single building model, each building case was simulated 10 times (n = 10) in both BaU and load-shift scenarios. Each *eplusout.csv* file contained the output variables listed in table 41 (left column) for each timestep. The first step was to convert these into higher level outputs which matched DesignBuilder's pre-processed output so that the power for each end use could be determined (figure 36, box 5).

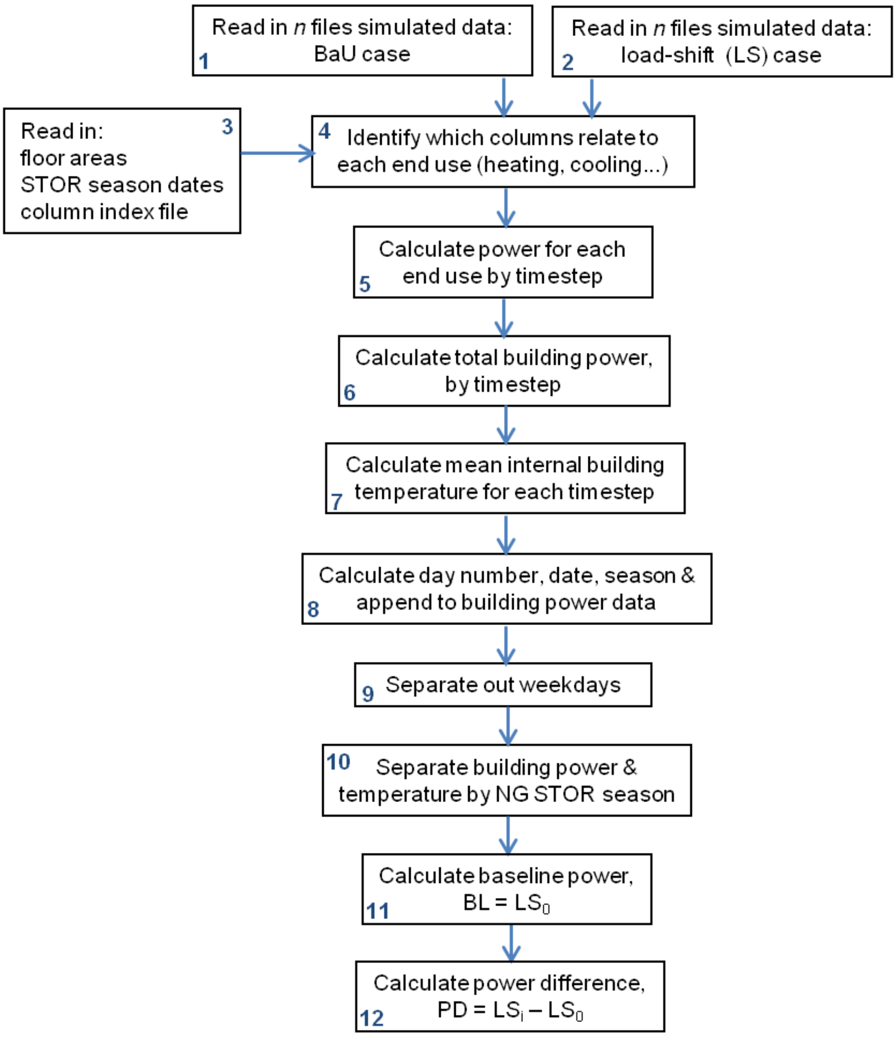


Figure 36 Analysis of single building simulations using Matlab

The mean internal building temperature was the temperature weighted by the area of each zone (equation 7). The heating and cooling fuel demands for the building, Ph and Pc were calculated by adding the ideal heating and cooling loads for each zone and applying the CoP values values (Equation 8 and Equation 9). The hot water power requirement was calculated by summing the hot water loads for each zone and applying the specific heat capacity, temperature difference and efficiency of the heating system (Equation 10). The power for lighting and IT was calculated by dividing each value for IT and lighting energy by the length of the timestep (Equation 11).

Table 41 Calculations on EnergyPlus Output Values

	EnergyPlus Output	Calculation	Calculated Value
1	Zone Mean Air Temperature [C] (Taz1 ... Tazn)	Mean internal building temperature (Ta)	$Ta = \frac{(A1.Taz1 + A2.Taz2 + \cdots)}{(A1 + A2 + \cdots)}$ Equation 7 An is floor area of zone n
2	Ideal Loads Total Heating Rate [W] (Qhi) (value for each zone)	Heating system power for building, Ph (kW)	$Ph = \frac{\sum_{i=1}^{n} Qhi}{\eta_h . 1000}$ Equation 8 η_h, CoP of heating system
3	Ideal Loads Total Cooling Rate [W], (Qci) (value for each zone)	Cooling system power for building, Pc (kW)	$Pc = \frac{\sum_{i=1}^{n} Qci}{\eta_c . 1000}$ Equation 9 η_c, CoP of cooling system
4	WaterSystems:Water [m^3] (value for each zone) Vi volume of DHW in zone i	Power to heat domestic hot water (DHW) for the building, Pw (kW)	$Pw = \frac{\sum_{i=1}^{n} Vi.1000.Cp.(T_{out} - T_{in})}{\eta_w . I.60}$ Equation 10 Cp heat capacity of water T_{in}, T_{out}, inflow and outflow temperatures of water η_w, efficiency of DHW heater *I*, length of timestep (10 minutes)
5	Electricity:Facility [J], (El)	Power for lighting and IT for building, Pl (kW)	$Pl = \frac{El}{I.60.1000}$ Equation 11

Source: *DesignBuilder (2011)*

Heating and cooling were setback on weekdays (section 6.3.4). Weekdays which provided the potential shiftable load, were separated out and disaggregated by season (boxes 9 and 10 in figure 36). The '*power difference*', was calculated by subtracting the building electrical power for the 10 minute timestep before the start of the load-shift period (LS_0) from all other values for the load shift period (LS_i) (equation 12).

$$PD_i = LS_i - LS_0\ (kW)$$ Equation 12

This was based on the methods used for calculating baseline load for STOR (section 4.4.1) and for a DNO DSM service trial (section 4.4.3). This is illustrated by the following example for a type 1 building (narrow plan, open plan) with poor insulation (1970s) and electric heating and cooling. The heating and cooling setpoints were 22°C and 24°C. Figure 37 to figure 39 form a sequence which illustrate the effect of setting back the heating and cooling for one hour (17:00 to 18:00). Figure 37 shows the electrical load for one day; figure 38 shows the change in electrical load for each day in the coldest STOR season and figure 39 illustrates how these data were used to calculate the load reduction.

The building electrical demand for part of 3rd December is shown in figure 37. The heating and cooling were setback from 17:00 to 18:00 ('the load shift' period). The '*DSM potential*' was calculated as the difference between the electrical demand during the timestep immediately before the start of the DSM period and the demand at the end of this period. In this example, the building electrical demand from 16:50 to 17:00 was 89.3 kW. The demand from 17:50 to 18:00 was 50.3 kW. This gives -39 kW as the *DSM potential*.

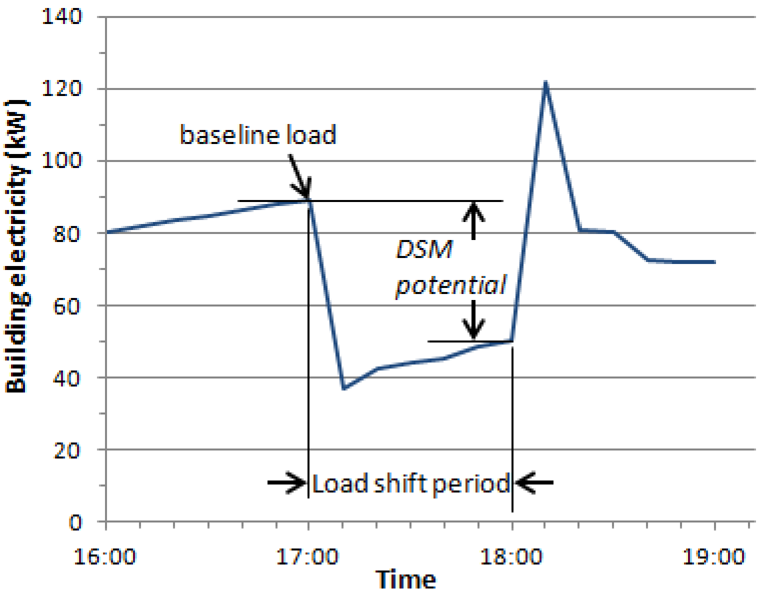


Figure 37 Calculation of electrical load shift due to heating and cooling setback, illustrated for a type 1, 1970s building with electric heating

Figure 37 illustrates the calculation of *DSM potential* for a single day with one set of building parameters (chosen from table 31 in section 6.3.5). Variation in the weather and differences in the heating and cooling setpoints were expected to affect the load shift potential. Electricity companies that purchase DSM services need to be confident that the service that they contract will be delivered. In the case of STOR, National Grid recognise this with penalties for non-delivery below 95% of the expected energy (section 4.4.1). DNOs are likely to expect the same level of service delivery (section 4.4.3).

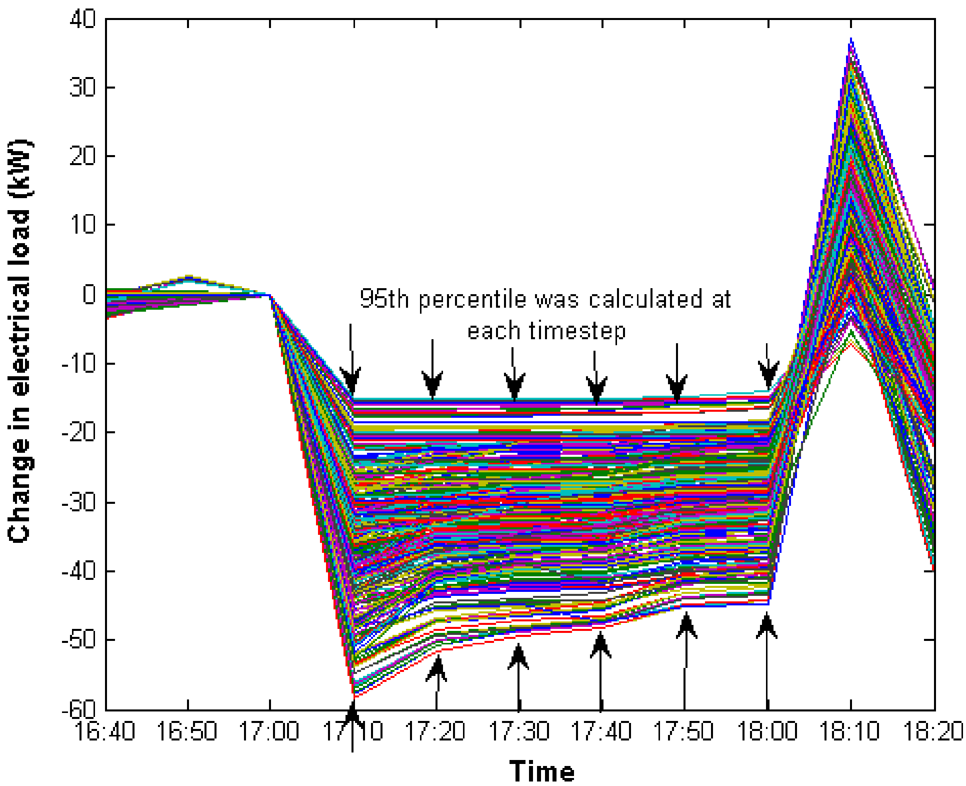


Figure 38 The difference between the electrical load at successive timesteps and the load at 17:00 (the baseline) for a type 1, 1970s electric heated building, for 27th October to 2nd February 2015 (season 5). There were 10 simulations with different parameter values, giving 68 days x 10 iterations (=680 values for each timestep). The 95th percentile of change in electrical load was calculated at each timestep and used as the indicator for DSM capacity.

The above requirement was recognised in this research by making the 95th percentile of power difference the threshold for assessing the DSM potential from the modelled buildings. This was calculated for each National Grid STOR season. Figure 38 shows the difference between the building electrical load at timesteps before, during and immediately after the load shift period and the load at the start of this period (17:00). This is for the same building as figure 37 (type 1, 1970, electrically heated) but shows the variation from 27th October to 2nd February 2015 (season 5), consisting of 68 weekdays. Ten iterations were carried out with different parameter values (heating and cooling setpoint and building orientation), which gave 10 x 68 (=680) values for each timestep. The 95th percentile of the power delta values were calculated at each timestep to indicate the DSM potential.

For the load-shift period (17:00 to 18:00), the 95th percentile, median and inter-quartile range (IQR) of power difference were plotted for each timestep. This generated one plot for each STOR season, with one ‘box’ for each timestep. Figure 39 illustrates this for a type 1, 1970s building with electric heating for 27th October to 2nd February 2015 (STOR season 5). Each box represents the inter-quartile range: the distance between the 25th and 75th percentiles. The black dotted line is the 95th percentile of power difference. The power difference at the final timestep of the DSM period was taken as the ‘DSM potential’ for a one hour DSM period. This was used to compare the results across the 24 cases (figure 61 and figure 62 and table 56 in section 7.2.3).

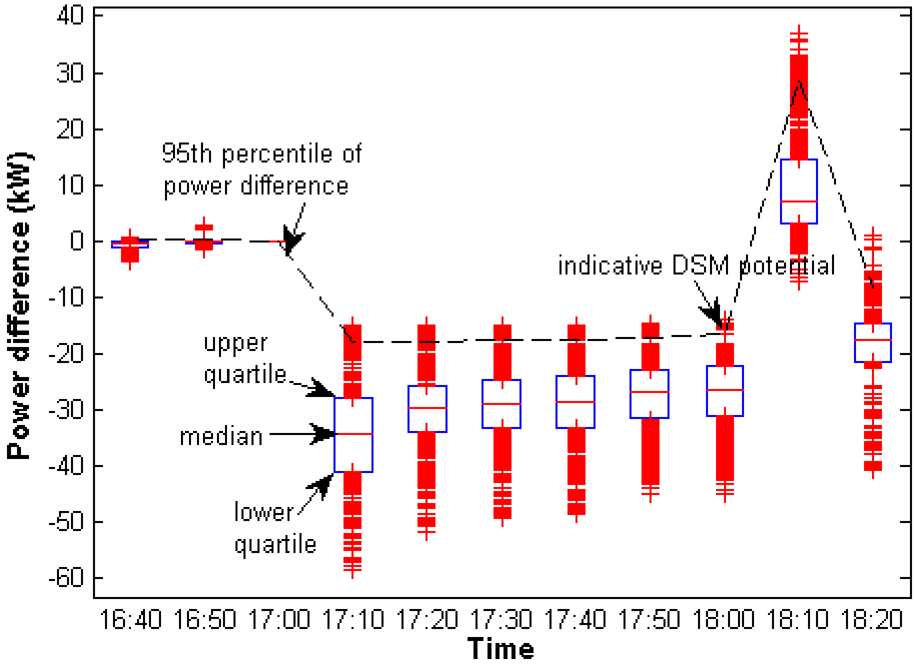


Figure 39 Boxplot for a type 1, 1970s building with electric heating for the period 27th October to 2nd February 2015 (season 5). ‘Power difference’ is the building electrical power at any timestep minus that at the timestep prior to the start of the DSM period (17:00).

The electrical load for the group of buildings was calculated by adding the power for each timestep (equation 13). Percentiles were calculated using the ‘*prctile*’ function in Matlab (Mathworks n.d.).

$Pt = \sum_{i=1}^{n} Pi$ Equation 13

6.3.9 Comparison of Model Data with External Sources

The model output was compared with measured data, following the process in figure 40. Simulated BaU electrical power profiles were compared with metered electricity consumption from buildings in Reading. The simulation cases and the example buildings were selected to be similar in terms of age band, built form type and HVAC, table 42. Data from these building cases were normalised by the building area for that type, table 21. The electricity consumption (kWh) was calculated for each half-hour period. Data for weekdays in each NG STOR season were separated out and compared with equivalent data from the example building.

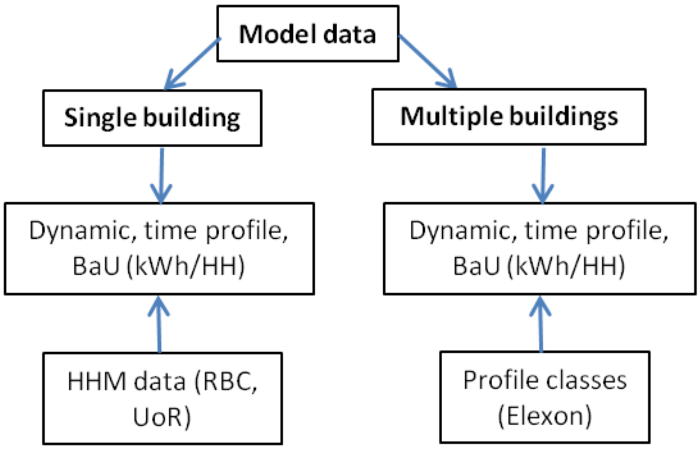


Figure 40 Comparison of data from simulations with external sources

Table 42 Buildings used for annual energy comparison

Simulation	Example Building
Case 16 1980's, deep plan, open plan Gas / electric heat & cool via FCU	Reading central library Constructed: 1985 Total useful floor area: 3389 m^2 2 floors open plan; 2 floors cellular Main heating fuel: natural gas Environment: mixed mode with natural ventilation
Case 23 1990's, deep plan, cellular Electric heat and cool from ASHP via FCU	Carrington Building, University of Reading (UoR) Constructed: 2007 Total useful floor area: 2224 m^2 Mixed open plan and cellular Heating: ASHP Environment: heating and natural ventilation

Source: *Display Energy Certificates*

For the simulations of multiple buildings, the electricity consumption in Category 2 (office buildings up to year 2000 in Reading Borough) (section 6.4.1) was compared with data for Elexon profile class 3 (section 4.2). Class 3 represents small commercial consumers with un-switched loads (Elexon 2013a). The comparison was made for '*winter weekdays*' since this covers the peak period when the main requirement for DSM occurs. The Elexon data consists of multiple sets of regression coefficients to cover each day type (weekday or weekend) and season (section 4.2). Each day is divided into 48, half-hour settlement periods. A year has five seasons (spring, summer, high summer, autumn and winter). Elexon define 'winter' as *'the period from the day of clock change from British Summer Time (BST) to Greenwich Mean Time (GMT) in October, up to and including the day preceding the clock change from GMT to BST in March'* (Elexon 2014). This evaluates to 26th October 2014 to 28th March 2015.

Electricity demand profiles were generated by the model for the aggregate electricity consumption of Category 2. A comparison was made between the mean electricty profile from the model and one calculated using Elexon regression coefficients. The mean consumption from the model for one weekday, (E_{dy}), was divided by the sum of the regression coefficients for winter weekdays (R_{wd}) to give the consumption in MWh per regression unit (e_n). The consumption for each settlement period, El_i, was calculated, where r_i is the profile coefficient for each settlement period:

$El_i = r_i . e_n$ (MWh) Equation 14

The 'Elexon' profile (equation 14) was compared with the model profile.

6.3.10 Sensitivity Analysis

An investigation was carried out to test the sensitivity of the shiftable load to three input factors. Timestep size, the number of simulations and the effect of building internal thermal mass were separately varied in order to determine the effect on the shiftable load.

6.3.10.1 Size of timestep

The timestep size was chosen to be 10 minutes. This was selected to give a reasonable number of points within each one-hour load-shift period. The aim was to capture most of the variation in power difference, in order to get a reliable estimate for a DNO or system operator DSM service. Other limiting factors were the timestep size of measured building data and of the weather file. Electricity consumption data, measured in actual buildings was only available at 30 minute timesteps due to half-hour metering. The weather file had 1 hour timesteps (section 6.3.6). Timesteps shorter than 10 minutes were evaluated in the investigation below.

The electricity consumption in one building was simulated 100 times with 1, 2, 5 and 10 minute timesteps for the load-shift scenario in table 43. This was investigated by simulating a type 2, 1980s building with gas heating and electric cooling (case 4 in table 39). This represented the most common geometric form (narrow plan, cellular) with the more common HVAC type and 35% of the office buildings in Reading (section 3.5.4). The simulations were carried out for January, representing the winter when the demand for DSM is greatest and for July representing the warmest time of year when the DSM opportunity with an electric cooling system is greatest. The median, 90th and 95th percentiles of the power difference were evaluated (table 43). Only weekdays were analysed since the building had low occupancy at other times.

Table 43 Parameters for evaluation of timestep size

Case 4	Period	Load shift	Analysis
Type 2, 1980 HVAC: gas / electric	(1) 1st to 31st January (2) 1st to 31st July	17:00 to 18:00 daily	Power difference (kW): median, 90th, 95th percentiles

Figure 41 shows the power difference for working days in July, for (a) 10 minute and (b) 1 minute timesteps. These simulations were carried out 100 times with a random selection of parameter values (heating and cooling setpoint and building orientation) in order to indicate the likely variation in power difference. This generated 100 representations of each of the 23 working days in July, making (100 x 23 =) 2300 lines on each plot. The reduction during the load-shift period was of interest rather than the power ‘spike’ after returning to the ‘normal’ setpoint. This ‘trough’ between 17:00 and 18:00 (figure 41) is the section that would relate to the electricity company DSM requirements. It was understood that small timesteps were required to capture the ‘spike’.

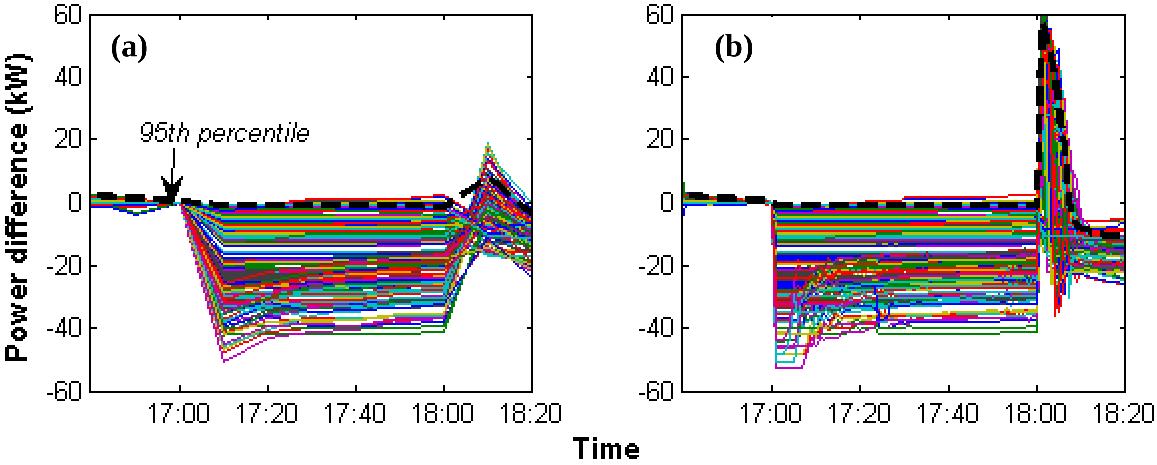


Figure 41 Power difference for July for a type 2, 1980s building with gas heating, when simulated 100 times with (a) 10 minute timesteps; (b) 1 minute timesteps. This represents 23 working days x 100 simulations. The 95th percentile indicates the threshold for DSM service.

Table 44 Median, 90th and 95th percentile values for 10 and 1 minute timestep simulations for July.

10 minute timesteps			1 minute timesteps		
median	90th percentile	95th percentile	median	90th percentile	95th percentile
-18.87 kW	-1.56 kW	-1.18 kW	-18.41 kW	-1.55 kW	-1.18 kW

The 10 minute timesteps capture the change in power difference for most of the load shift period but not the transient spikes at the start and after the return to normal. The median, 90th and 95th percentile values were calculated for each timestep. The maximum values of these indicators were calculated for the load-shift period, table 44. This indicates the load shift that could be offered as part of a DSM service for one hour. The difference between the 95th percentile values for 1 minute and 10 minute power difference is zero. Since the criteria for determining the shiftable load were the 95th percentiles, 10 minute timesteps were considered close enough.

Figure 42 shows the power difference for each timestep for each simulation for January with (a) 10 minute timesteps and (b) 1 minutes timesteps. The maximum values of the median, 90th and 95th percentile of power reduction during the load shift period are given in table 45. The difference between these maxima for 10 and 1 minute timesteps is zero. No cooling was required during this period. The only load reduction with this model case was due to the reduction in power of HVAC pumps. In the model, the power consumed by pumps was deterministic, which resulted in no power variation. Since the criteria for determining the shiftable load were the 95th percentiles, 10 minute timesteps were considered close enough.

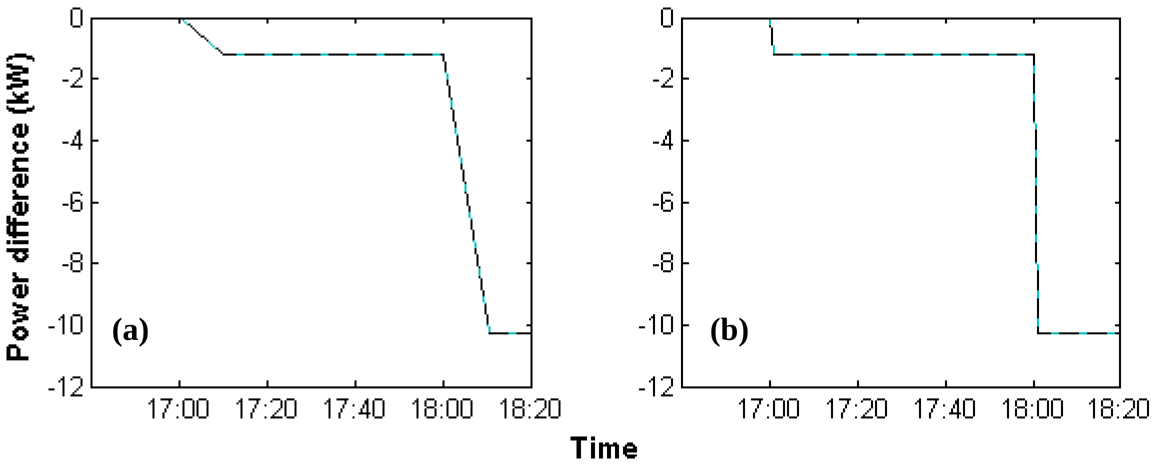


Figure 42 Power difference for January for a type 2, 1980s building with gas heating, when simulated 100 times with (a) 10 minute timesteps; (b) 1 minute timesteps. This represents 23 working days x 100 simulations. The 95th percentile indicates the threshold for DSM service.

Table 45 Median, 90th and 95th percentile values for 10 and 1 minute timestep simulations for January

10 minute timesteps			1 minute timesteps		
median	90th percentile	95th percentile	median	90th percentile	95th percentile
-1.18 kW	-1.18 kW	-1.18 kW	-1.18 kW	-1.18 kW	-1.18 kW

6.3.10.2 Number of simulations

The effect of the number of simulations on the power difference was investigated. This was relevant because the 'quasi-static' models in EnergyPlus 'average' the calculated values (temperature or energy, for example) over the duration of a timestep (section 6.3.6). The parameter values were randomly selected for each iteration (table 31 in 6.3.5). The effect of this was evaluated by simulating case 4 (type 2, 1980, gas heat / electric cool) for January and July as in section 6.3.10.1. The simulation was carried out 100 times. The first 10, 50 and 100 iterations were selected and the power difference calculated. For the load shift period, the 50th, 90th and 95th percentiles were calculated for each timestep. The maximum values of the 95th percentiles during the load shift period were calculated. Table 46 and table 47 show these values for July and January. For both months, the difference between 10 and 100 iterations was zero. This is surprising but is consistent with the results in figure 61 in section 7.2.3 which show power difference of -1.2 kW to -1.3 kW for these months for 1980s gas heated buildings. This is due to virtually no cooling requirement in these model cases. In comparison, the 1990s gas heated cases required significant cooling during July. In both cases, the difference was considered small enough that 10 iterations would be sufficient. This also reduced the computational effort.

Table 46 95th percentiles of power difference for July simulations

10 iterations	50 iterations	100 iterations
-1.18 kW	-1.18 kW	-1.18 kW

Table 47 95th percentile of power difference for January simulations

10 iterations	50 iterations	100 iterations
-1.18 kW	-1.18 kW	-1.18 kW

6.3.10.3 Thermal mass and insulation

Building thermal mass affects heating and cooling rates by storing and later releasing heat energy (section 3.5.1). The effect of thermal mass on shiftable load was tested with a type 2, 1990s building with gas heating (case 6 in table 39). Case 6 was chosen because it represented the most frequently occurring geometric type (table 4 in section 3.3.1), combined with the more popular HVAC type (gas heat / electric cool) and the most recent fabric standard of those evaluated. This case has a cellular layout, with internal plasterboard partitions separating adjacent zones (figure 17). These represent physical mass in contact with the internal air, which enable heat to be stored and later released. Table 48 lists the modifications made to the partition to investigate the effect of thermal mass. The base case consisted of the default values loaded by DesignBuilder. The density of the plaster was changed in order to determine how this would affect the power difference. Dense and light plaster were theoretical materials in which only the density had been changed. In a real material, other factors such as the conductivity would be expected to change. A solid concrete partition with no internal air gap was also tested. The specific heat capacity, C_p, of the three types of plaster and the concrete was 1 kJ/kg.K.

Table 48 Thermal mass test: parameters of partitions

Case	Construction	Density, ρ (kg/m^3)
Base case	2 layers plasterboard (25 mm each) with air gap of 100 mm	900
Dense plaster	2 layers plasterboard (25 mm each) with air gap of 100 mm	2000
Light plaster	2 layers plasterboard (25 mm each) with air gap of 100 mm	500
Concrete partition	Solid concrete, 100 mm	2000

The thermal capacitance values, C, and resistance, R, were calculated using equations 4 and 3 in section 6.3.6 for area, A = 1m^2. It was understood that the calculation of capacitance (equation 4) determined a value for one face of the partition. The air gap was ignored in this calculation. The R values were calculated for two layers of plasterboard and an air gap with thermal resistance of 0.15 m^{2}K/W (table 49). Table 49 shows that changing from the 'base case' to concrete partitions increased the thermal capacitance, C, by nearly nine times.

Table 49 Calculation of thermal capacitance and resistance

Scenario	Density, ρ (kg/m^3)	Thickness, *l* (m)	Conductivity, κ (W/m.K)	C (kJ/K)	R (K/W)
Base case	900	0.025	0.25	11.25	0.350
Concrete partition	2000	0.1	1.13	100	0.088
Dense plaster	2000	0.025	0.25	25	0.350
Light plaster	500	0.025	0.25	6.25	0.350

This example is for a type 2, 1990, gas heated, electrically cooled building (case 6) with different materials used to construct the internal building partitions. The *power difference* between the baseline electrical power (at 17:00) and the demand at each timestep was calculated, for each day simulated. The 95th percentiles of these values at each timestep were calculated (according to the method in section 6.3.8).

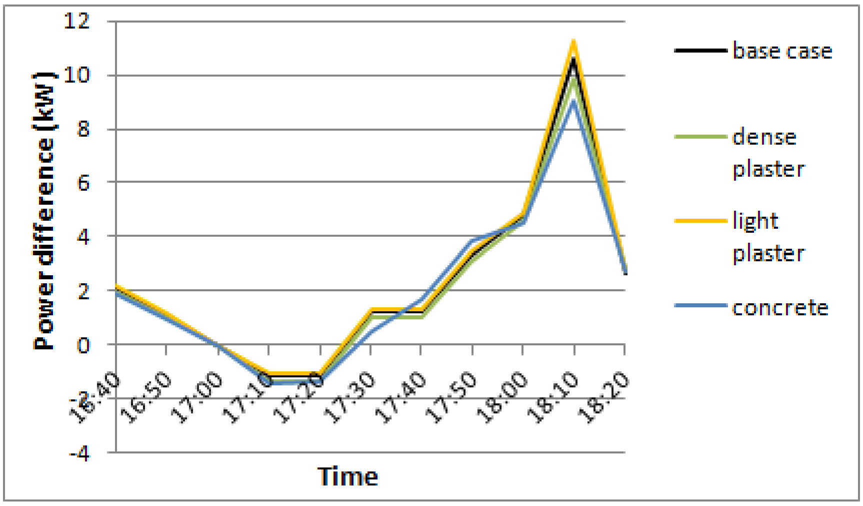


Figure 43 Effect of different partition constructions on power difference for the period 18th August to 22nd September 2014 (season 3), for a type 2, 1990s building with gas heating

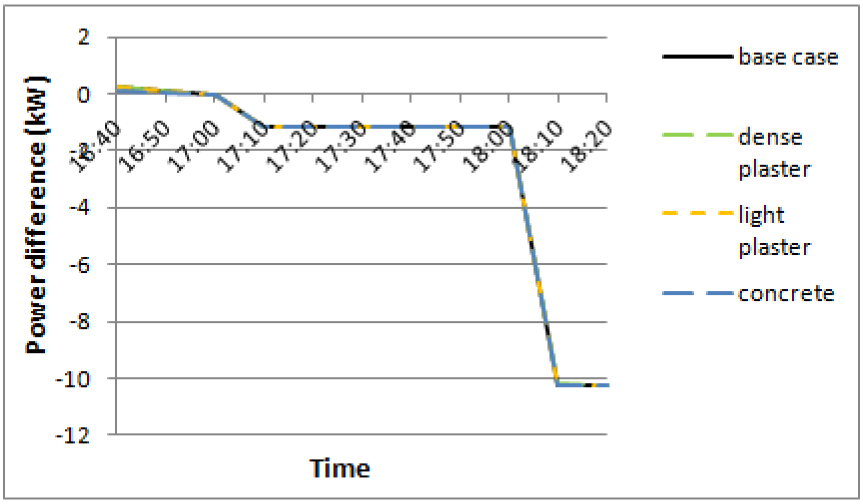


Figure 44 Effect of different partition constructions on power difference for the period 27th October to 2nd February 2015 (season 5) for a type 2, 1990s building with gas heating

Figure 43 shows the 95th percentile of the power difference for the period 18th August to 22nd September 2014 (season 3). Changing the density of the plaster had only a small impact on the power difference. The dense plaster and concrete resulted in slightly greater power reduction than the base case. The power reduction from the baseline level was sustained for around 5 minutes longer. The increase in electrical load after the DSM period was slightly less compared with the base case. Figure 44 shows the 95th percentile of the power difference for the period 27th October to 2nd February 2015 (season 5). Changing the density of the plaster had no impact on the power difference as the only flexible load was HVAC pumps.

6.4 Multiple Building Model

This section describes how a group of buildings is represented using simulations of individual buildings. The simulation scenarios were developed with the following factors in mind:

- The DSM requirements of the SO and DNOs (section 4.4)
- Office building data for Reading Borough (section 3.5.4)
- Results from the single building simulations (section 7.2)

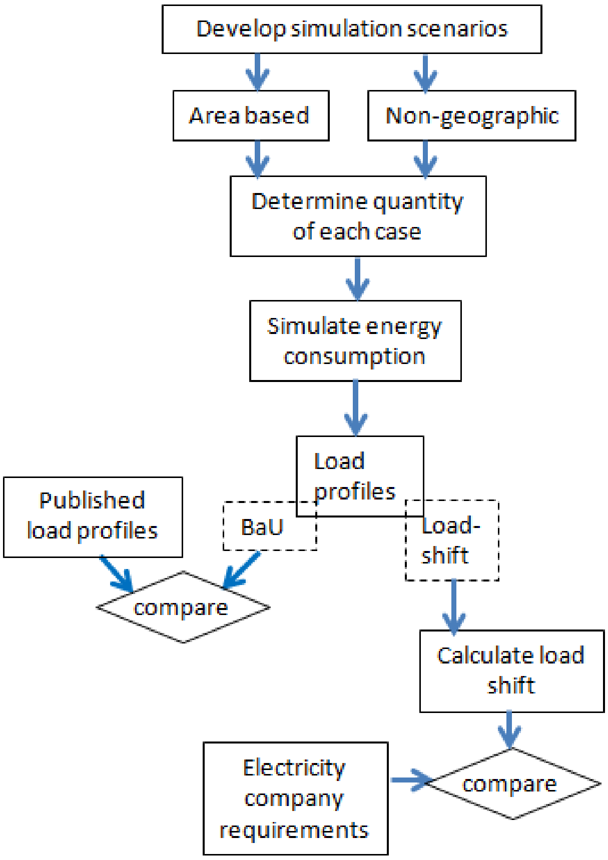


Figure 45 Process for representing groups of buildings

6.4.1 Development of the Multiple Building Model

Table 50 Categories for multiple building model

	Rationale	Simulation cases	Space & client
1	To identify largest load-shift from a group of buildings based on single building simulations	Type 1, 1970, electric heating and cooling (case 7)	Non-geographic SO
2	To represent a large proportion of office buildings in Reading Borough using 24 defined cases	All cases. Built form types in proportion to occurrence in Steadman (2000). Age bands from ODPM (2005) and Worringham (2004)	Geographic SO & DNO
3	To represent known office buildings within a 1 km diameter circle in Reading Borough (figure 48)	Cases to represent buildings in Worringham (2004). Built forms identified using Google Maps™ and local knowledge	Geographic DNO

The multiple building model uses the building cases developed in section 6.3. This section describes the scenarios and the calculations are detailed in section 6.4.2. Table 50 lists the simulation scenarios.

Category 1 represented a group of buildings with the largest DSM opportunity based on the results of the single building modelling. This created a hypothetical, non-geographic group of buildings, dispersed across the UK and could relate to the DSM requirements of the SO. Category 2 represents pre-2001 office buildings in Reading Borough, based on the analysis in section 3.5.4. The DSM client could be the SO or it may also support DNO peak reduction. This area was within the coverage of several sub-stations but a single DNO. Although distribution network constraints are often related to sub-station areas, sometimes larger urban areas are of concern as with the NTVV Project (Thames Valley Vision 2012). This was intended to be indicative of the potential load shift from a sizeable group of buildings in an urban area, not the total for all commercial buildings. Category 3 related to a geographically close subset of buildings in Reading, which could be served by a constrained DNO sub-station.

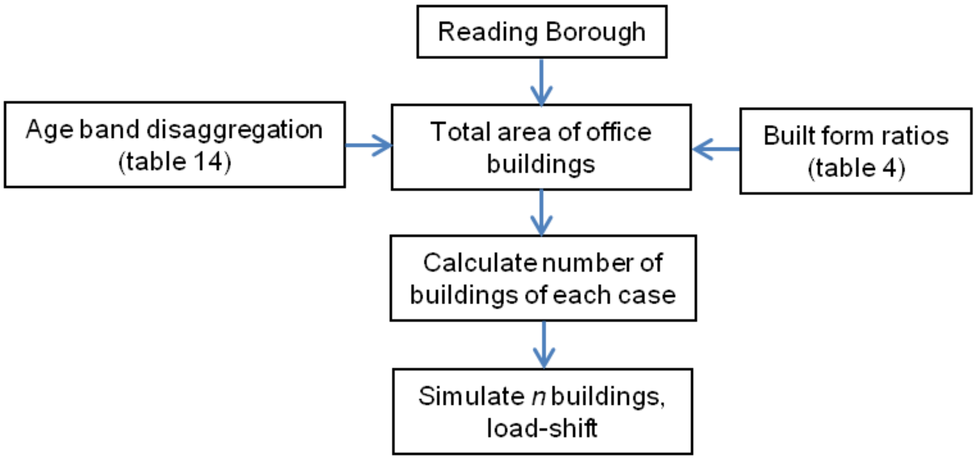


Figure 46 Representation of groups of buildings in a geographic area (Category 2)

Category 1 consisted of buildings from the case with the largest power difference. Section 7.2.3 shows that type 1, 1970's, electric heat and cool (case 7) had the largest power difference for STOR seasons 2, 5 and 6 (28^{th} April to 18^{th} August 2014 and 27^{th} October to 1^{st} April 2015). Since the highest demand for load reduction was during the winter, the number of buildings was based on the power difference during this period (27^{th} October to 2^{nd} February 2015, season 5). The 95^{th} percentile of the power difference for season 5 was 16.55 kW (table 56 in section 7.2.3). Assuming 3 MW minimum for STOR, this suggested that 182 of this case would be needed. This building case was simulated 182 times and the power difference was calculated.

Category 2 represented office buildings located anywhere in the Borough of Reading, based on the analysis in 3.5.4. The process in figure 46 was followed. The ratios of built form types (T_j), (table 4, right hand column, section 3.3.1) were multiplied by the floor areas of office buildings disaggregated by age band, table 14 (A_i) (section 3.5.4), to calculate the area of each type in each age band, A_n (equation 15).

$A_n = A_i . T_j$ (m^2) Equation 15

The input values, T_j and A_i are reproduced in table 51 and the calculated values of A_n in table 52.

Table 51 Proportion of built form types and floor areas used to determine the quantities of building archetypes in simulation Category 2

Proportion of Type in Office Buildings, T_j (table 4)		**Floor area of Offices in Reading by Age Band (x1000m^2), A_i** (table 14)			
		Up to 1980	**1981-1990**	**1991-2000**	**2001-2010**
Type 1	4.32%	140	200	128	97
Type 2	58.40%				
Type 3	8.20%				
Type 4	29.07%				

Source: *(Steadman, Bruhns, Holtier, et al. 2000; VOA 2012a)*

The values of A_n were divided by the internal floor area of each type, A_{tj}, ('Bldg area, GIA' in table 21 in section 6.3.1) to give the quantities of each archetype (equation 16).

$$N_{nt} = \frac{A_n x 1000 x 0.54}{A_{tj}}$$ Equation 16

A_{tj} is the gross internal area of each modelled type. The factor of *1000* converts from *thousands of m^2* to m^2. The '*0.54*' factor is because 54% of the floor area in each category (built form and age band) was assumed to have gas heating and electric cooling (section 3.5.3.1).

Table 53 gives these quantities of each archetype rounded to the nearest whole number for use in the simulation. Only office floor space constructed up to the year 2000 could be represented by these building cases. Mains gas was assumed to be present at all sites since coverage of the gas main is close to 100% (Khan & Stadnyk 2013).

Table 52 Breakdown of office space by built form type in Reading Borough by age band

	Up to 1980	**1981-1990**	**1991-2000**	**2001-2010**
	NIA (thousands m^2), A_n			
Type 1	6.05	8.65	5.53	4.18
Type 2	81.72	116.80	74.75	56.50
Type 3	11.47	16.40	10.50	7.93
Type 4	40.68	58.15	37.21	28.13

Table 53 Quantities of archetypes relating to gas heating and cooling, in Category 2

	Up to 1980	1981-1990	1991-2000	2001-2010
Type 1	2	3	2	N/A
Type 2	30	43	28	N/A
Type 3	4	6	4	N/A
Type 4	15	22	14	N/A

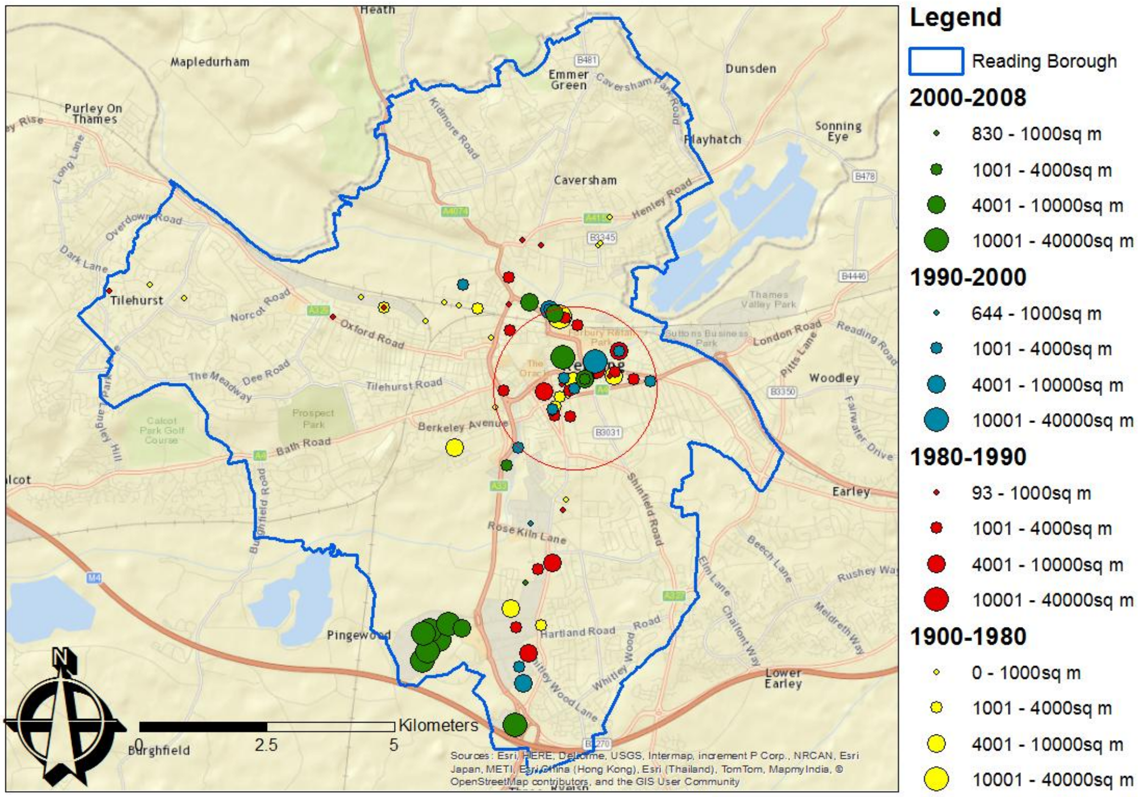
Model category 3 represented a small geographical area of Reading Borough with a high concentration of office buildings. This was taken as an illustrative area as no data on network constraints were available from the DNO. This group of buildings represented a *'load cluster'*, which could theoretically connect to a single DNO sub-station (Strbac et al. 2010). According to Strbac et al. (2010), the *'average network length associated with a distribution transformer in the GB system is about 1,450m'* and for '*SSE South'* (SSEPD) approximately 1100m. The radial distance from transformer to feeder end point is generally shorter due to cable routes following roads in urban areas. This was allowed for by dividing the network length by √2, giving a mean radial distance of 780 m for SSEPD. In this research, a circle of 1 km diameter was chosen to delineate the buildings of interest.

The individual office buildings listed in (Worringham 2004) (section 3.5.4) were plotted using ArcGIS™ (Esri n.d.), categorised by age band and floor area band, figure 47. A 1 km circle with a high concentration of pre-2001 buildings was selected for investigation (red circle in figure 48). The post code of each building was entered in Google Maps™ (Google 2015) to determine the plan type (narrow or deep). Those that could be identified all appeared to be narrow plan. The division of space (cellular or open plan) could not be determined by external inspection but the most common type, in the NDBS Project (table 4 in section 3.3.1), was narrow plan cellular. This was represented by type 2, so all buildings were assumed to be of this type. Table 54 gives the net internal area of these buildings by age band.

Table 54 Floor areas and quantities of simulated buildings (Category 3)

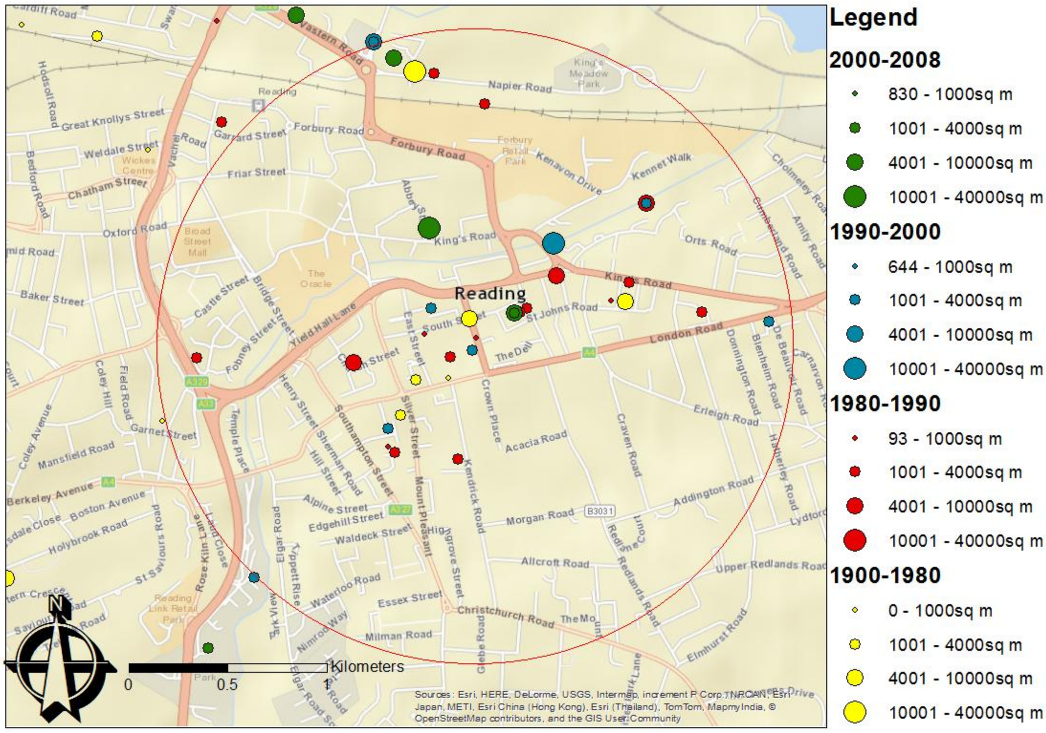
	1970s and earlier	1980s	1990s	2000s
Building floor area, NIA (m^2) *(Worringham 2004)*	9216.5	23746.92	22690	4889.23
Quantity of Type 2 buildings	6	16	16	N/A

The modelled building cases represented floor space constructed before the year 2001. In Category 3, the proportion of the floor area in each age band with gas heating and electric cooling was assumed to be 100% in order to calculate the maximum potential for load shifting. It was recognised that the true proportion would be less than this but each building would have to be surveyed to determine the HVAC type. The quantity of type 2 buildings for each age band was calculated by dividing the floor areas in table 54 by the area of a type 2 building. The area used in this calculation was the gross internal area (GIA) (1453 m^2), as with simulation Category 2. The quantities of type 2 buildings used in the model were rounded to the nearest whole number (table 54). This scenario indicated the opportunity for load shifting from a defined area.



Credit: *McCausland (2015)*. Source: *Worringham (2004)*

Figure 47 Office buildings in Reading Borough listed in Worringham (2004)



Credit: *McCausland (2015).* Source: *Worringham (2004)*

Figure 48 Office buildings selected for scenario 3

6.4.2 Analysis of Multiple Building Simulations

The building simulations were carried out using jEPlus to interface to EnergyPlus (figure 21). A weather file for London Gatwick was used with all simulations. With category 1, Type 2, 1970 electric was simulated for one year, 182 times with parameters randomly selected using the LHS option in jEPlus. This was done for the load shift scenario only (with HVAC setback from 17:00 to 18:00 each day). With categories 2 and 3, each building case was simulated *n* times in BaU and load shift scenarios. '*n'* is the quantity of each building case shown in table 53 or table 54 (Category 2 or Category 3 respectively).

The purpose of this study was to quantify the load shift potential and compare this with the requirements for DSM from the SO and from a DNO. The requirements for DSM from DNOs are less clear, since this is at the evaluation stage (section 4.4). WPD's Project Falcon was taken as an example of DSM and used as the basis for the calculations below (Swandells 2014). The calculations detailed in section 6.3.8 were carried out on the simulated data in order to determine the power difference and the baseline consumption for each timestep. Sections 6.4.2.1 and 6.4.2.2 detail the calculations related to STOR and DNO services.

6.4.2.1 Calculations related to National Grid's STOR Service

The calculations in this model follow the steps below, which are based on those for calculating payment for STOR (National Grid 2009) (section 4.4.1). With STOR, the 'baseline' power is the mean demand for 4 minutes before the instruction to commence load reduction. With this research, the baseline was the power consumption during the (10 minute) timestep immediately prior to the start of the load shift period. This model assumed that the entire DSM period (17:00 to 18:00) was non-ramp and that the load shift service could always be delivered immediately. It was thought most likely that companies unfamiliar with STOR would require at least 20 minutes notice period was required. The availability and utilisation payments reflect this. However, some companies may be able to respond more rapidly and the calculations also show the revenue in this scenario.

The contracted power, Pc, was assumed to be 3 MW since this is the minimum delivery under STOR. For a group of *m* buildings, the total power demand, Pt, was calculated by summing the power of each building, Pb, for each timestep during the load shift period (Equation 17):

$Pt = \sum_{i=1}^{m} Pb_i$ (MW) Equation 17

Calculate baseline consumption (BL). This was the building power consumption for the timestep immediately prior to the start of demand reduction (Pt_{-1}). The entire DSM period was regarded as non-ramp (section 4.4.1).

Calculate the expected energy per timestep, E_e (MWh), where I_v was the length of a timestep (10 minutes). Sum the expected energy for each settlement period (SP) (30 minutes) and round to 3 decimal places (Equation 18):

$E_e = \sum_{i=1}^{n} \frac{I_v}{60} . P_c$ (MWh) Equation 18

Calculate the delivered energy per timestep (D_e). Pt_i was the power of the group of buildings at timestep *i*. Sum this for each settlement period and round to 3 decimal places (Equation 19):

$D_e = \sum_{i=1}^{n} {(Pt_i - BL).I_v}/{60}$ (MWh) Equation 19

The capped energy, E_c is the minimum of the expected energy and delivered energy. This is calculated for the entire load shift period (Equation 20):

$E_c = \min(E_e, D_e)$ (MWh) Equation 20

To ensure that the energy delivered was at least equal to the contracted energy, the 95th percentile of delivered energy was calculated for each SP.

The *availability* payment, A_p, (equation 2) was calculated using the following rates from section 4.4.1:

for providers requiring at least 20 minutes notice, £0.65 / MWh; for providers requiring less than 20 minutes notice, £1.80 / MWh.

Calculate the *utilisation* payment, U_p, where U_r is the utilisation rate (£). This was only possible for the non-ramp period:

$Up = E_c . U_r$ (£) Equation 21

For providers requiring at least 20 minutes notice, the utilisation payment was £90 / MWh; for providers contracted to provide a service with less than 20 minutes notice, £139 / MWh.

6.4.2.2 Calculations related to a DNO DSM service

The calculations in this model relate to a potential DNO DSM service and follow the steps below. These are based on the payment calculations for WPD's Project Falcon trial service, described in section 4.4.3. The calculations in this analysis were as follows:

(1) Calculate delivered energy for each timestep, Di

(2) Calculate average delivery during the load-shift period. The contracted power, Cm, was assumed to be zero as no minimum was stipulated.

(3) The capped delivery taken was the same as average delivery.

(4) Calculate the cumulative delivery in MWh for DSM event, Dc.

(5) The benchmark for availability and utilisation is at least 95% (section 4.4.3). Calculate the 95th percentile of Dc for all weekdays in season.

(6) Calculate payment which is made for utilisation only: Pu= D x £300.

6.5 Conclusion

A method was developed to quantify the discretionary electrical load from groups of office buildings, by combining simulations of individual buildings. A building physics approach with a reduced set of parameters was chosen as proposed in chapter 5. Analysis of the literature in chapter 3 identified four built form types which were adopted in this study and used in combination with three building age bands. Heating and cooling were identified in chapter 3 as the most significant sources of flexible load in office buildings. To investigate this, two current scenarios were developed, each with a representative HVAC system type: '*current*' with gas heating, electric cooling and mechanical ventilation and an '*alternative*' scenario with electric heating, cooling and mechanical ventilation. The model values relating to the building fabric, HVAC, indoor environment and schedules were explained. 'Parameter' values which represent variation in key factors affecting heating and cooling demand were described; these were heating and cooling setpoints and building orientation.

The accuracy of the model input data was verified by calculations and example simulations which compared sample model output with data from DECs and ECUK. For the gas heated cases, the annual energy consumption was close to the DEC data; for the 1970s cases, it was 35% to 38% greater and for the 1990s cases, 30% lower. The energy consumption of the electrically heated cases was between 33% less and 8% more than benchmarks, due to the higher CoPs for heating and cooling. Sample temporal plots of model outputs were related back to the 'driving' inputs. For example, the internal temperatures in office zones were compared with the external temperature and showed that it remained within the specified thresholds. The power consumption of electric lighting was compared with the solar gain and showed the expected reduction as daylight increased.

Sensitivity tests were carried out on timestep size, number of simulations and thermal mass. 10-minute timesteps captured the power difference during the load shift period. Ten simulations captured the variation in power difference in the example considered. The effect of substantially increasing the thermal capacitance of the internal building partitions was a slight increase in the duration of the load reduction from the baseline level when cooling was required.

The model of a group of buildings was developed from the single building simulations. Test scenarios relating to System Operator and DNO needs were described which map to either geographically dispersed or location specific building groups. The following chapter illustrates key results from simulations on single buildings and clusters.

7. Simulation Results

7.1 Introduction

Chapter 5 established the need for a model to quantify DSM potential in buildings. Discretionary electrical loads from heating and cooling loads would need to be aggregated across several buildings in order to make enough load. A model was developed in chapter 6 to determine shiftable loads from groups of buildings by simulating individual buildings. This model was developed using EnergyPlus and the results analysed in Matlab.

This chapter shows results from these simulations. Simulations of single buildings are presented first, followed by results for groups of buildings. Sample results of particular relevance are presented first followed by tests on the validity. The simulation scenarios were developed to test under what conditions a DSM service supplied by multiple office buildings might be of the appropriate scale to fit the requirements of the System Operator or a DNO. Selected results are shown below and discussed in chapter 8.

7.2 Single building results

Each of the 24 building cases listed in table 39 (section 6.3.8) was simulated in business as usual (BaU) and load shift scenarios ten times. These consisted of four built form types x 3 building age bands x 2 HVAC types. This is illustrated with sample results which show raw data in this section, followed by analysis of the potential for DSM (section 7.2.3).

7.2.1 Analysis of Model Output

The effect of setting back heating and cooling is illustrated in figure 49 and figure 50 for a poorly insulated building with gas heating (case 2 in table 39). The modelled building had high heat loss due to low level insulation (1970s fabric) and due to its geometry (narrow plan, type 2). The heating and cooling setpoints were 22°C and 24°C respectively and the outside temperature was between -6°C and 10°C during this period (2nd to 6th December). The temperature of one office area on each floor (zone 1a) and the building mean are shown in figure 49. During *occupied hours* (08:00 to 18:00 on weekdays, section 6.3.4), the temperature of each zone was maintained at 22°C except for the DSM period of 17:00 to 18:00, when it was constrained within the load shift setback thresholds of 19°C and 26°C. The mean temperature was lower since the setback temperature in non-working areas was 16°C.

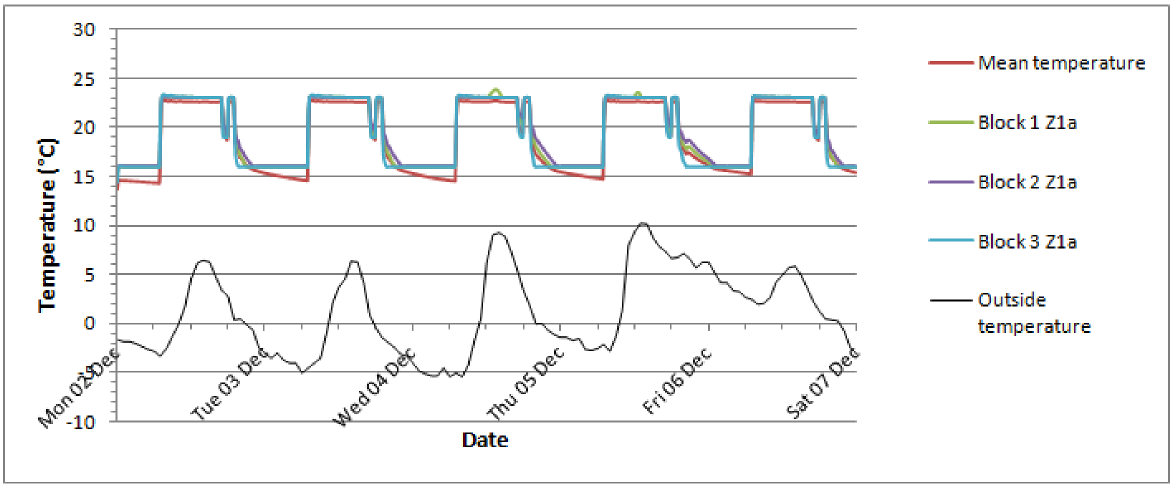


Figure 49 Internal temperatures for a type 2, 1970s building with gas heating from 2nd to 6th December with load shift each weekday from 17:00 to 18:00. This compares the building mean (red line) with one office area on each floor (zone 1a) and the outside temperature.

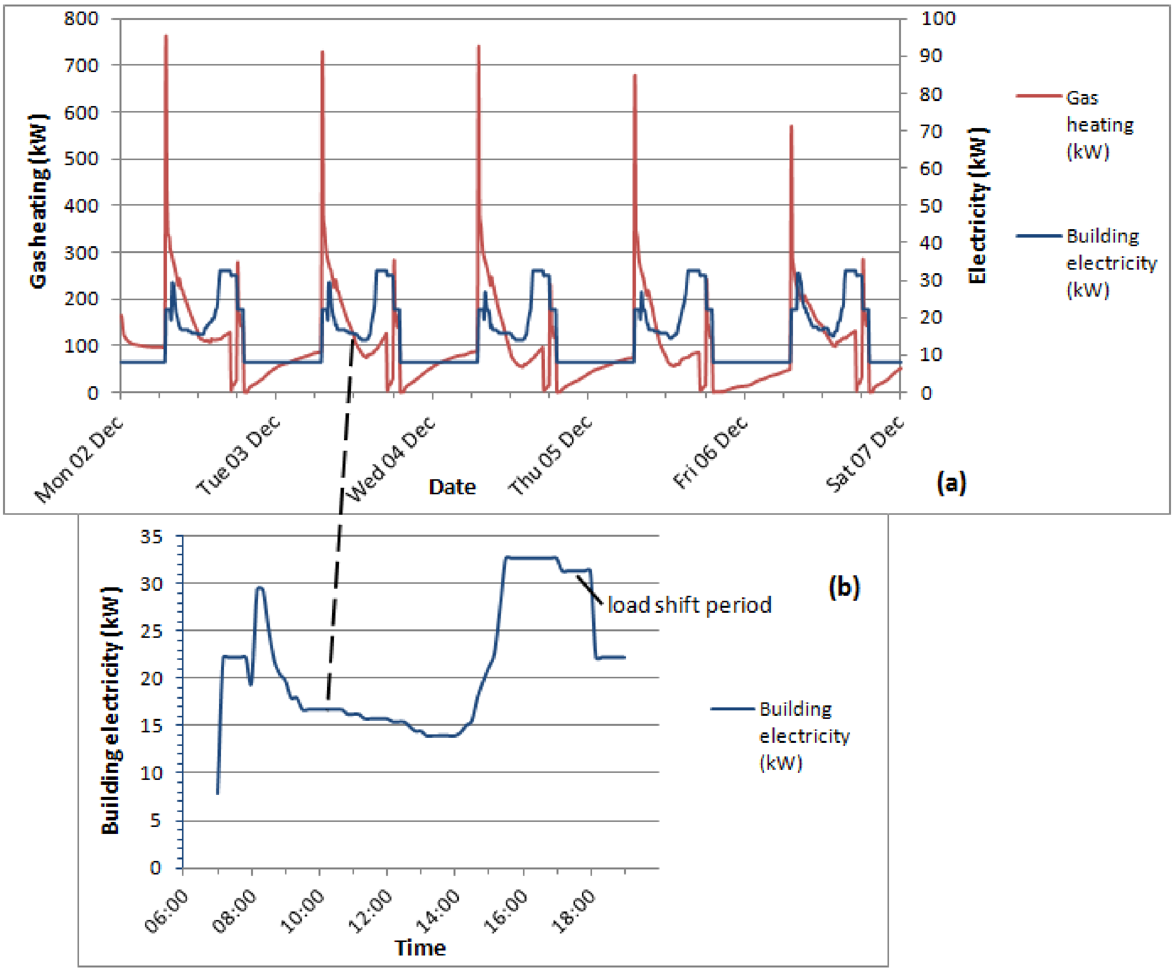


Figure 50 Heating and total electrical load for a type 2, 1970s gas heated building with load shift from 17:00 to 18:00 (a) 2nd to 6th December (b) electrical load for 3rd December

The demand for gas for heating to maintain these temperatures is illustrated in figure 50. The ‘spike’ at 07:00 each morning coincides with the scheduled time for heating to start and a smaller peak at 18:00 each weekday reflects the end of the DSM period, as the building temperature returns to the setpoint level (from the setback level). ‘Building electricity’ in this example consists of lighting, IT and HVAC fans and pumps. No cooling was required on these days. Artificial lighting was determined by a time schedule and by ambient daylight (section 6.3.4). HVAC fan power was set in proportion to the occupancy schedule, which stated that after 17:00, only half the occupants were present (section 6.3.4). HVAC pumps were set to reduce by half during load shift periods (17:00 to 18:00) (section 6.3.3.3). This reduction in fan and pump power load accounted for the reduction of 1.3 kW from 17:00 to 18:00. The larger reduction after this was due to IT being reduced as staff started to leave at the end of the working day.

The comparison of a model case with Reading Library (section 7.2.5) showed an unexpected afternoon peak in electrical demand on warm afternoons and a ‘dip’ during the middle of the day on cool days. This was investigated below. Figure 51 illustrates the median electrical demand for cooling and lighting for a type 3, 1980s gas heated building during the summer and winter. During the period (28th April to 18th August), the cooling increased during the afternoon. During the night, the power demand for lighting, IT and HVAC fans and pumps was nearly 8 kW, due to the scheduled out of hours lighting and IT (section 6.3.4). Figure 51b shows the median electrical power during cooler months when almost no cooling was required. During this period (27th October to 2nd February), the lighting and IT power decreased during the middle of the day. This is due to the electric lighting being reduced in response to greater levels of daylight. Figure 52 shows the breakdown of electricity consumption for this model case for three days in December. There was no demand for cooling during this period. The electric lighting decreased during the daytime as daylight increased and this resulted in the ‘U-shape’ in the overall demand in figure 51b.

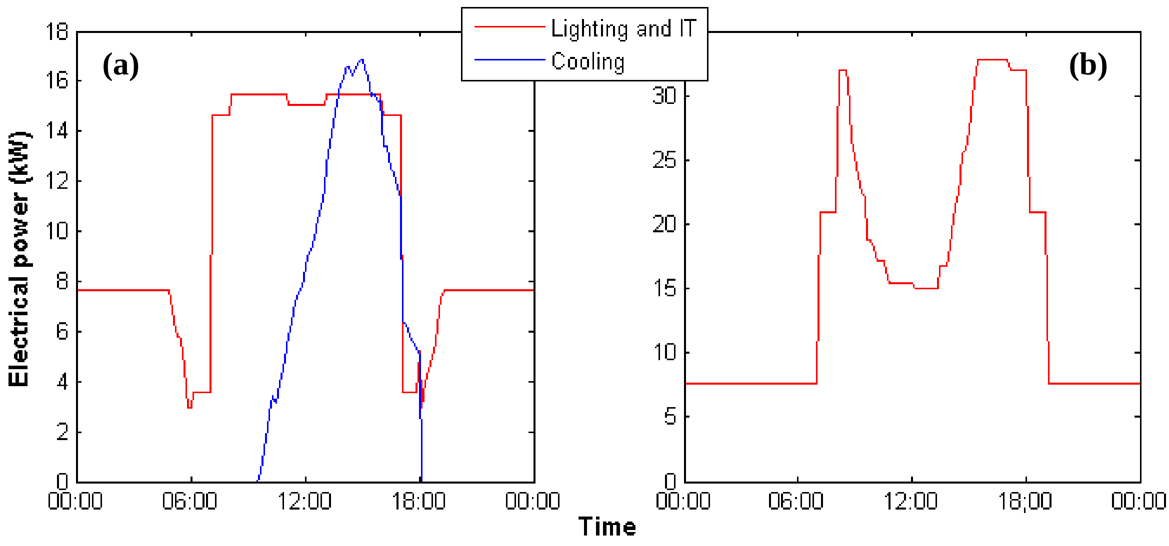


Figure 51 Median electrical power for lighting, IT and cooling for a type 3, 1980s building with gas heating for (a) 28th April to 18th August (Season 2) and (b) 27th October to 2nd February (Season 5)

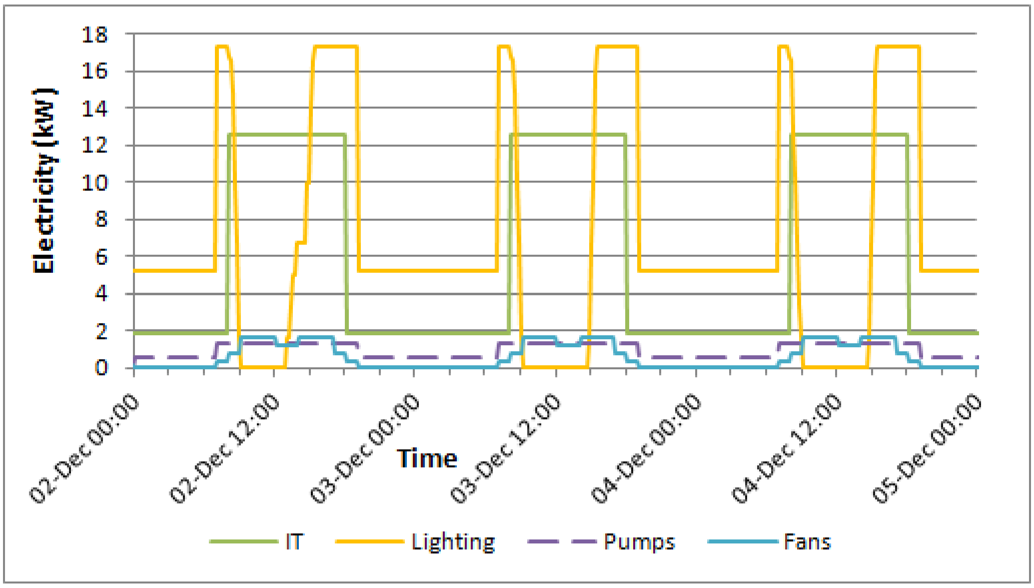


Figure 52 Electricity consumption for a type 3, 1980s building with gas heating in *business as usual* scenario, during December

During Spring and Autumn, the reduction in electricity demand during load shift periods was small and in some instances, there was a net increase in mean demand over a month (figure 61 and figure 62). The electricity consumption was investigated for April and October when the heating and cooling loads were low. During October, cooling was required on a small number of days, related to the outside temperature, figure 53. The better insulated, 1990s buildings required more cooling than the 1970s buildings, which resulted in more days when the building load was reduced in response to a DSM request.

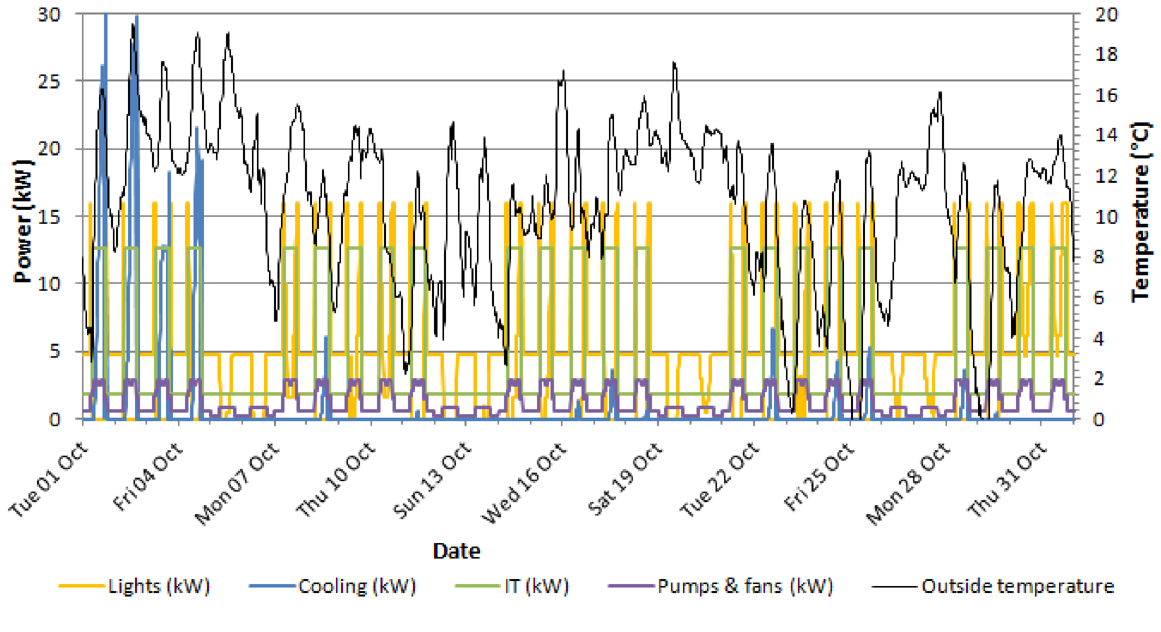


Figure 53 Breakdown of electricity by end use in the *load shift* scenario for a Type 1, 1990s, gas heated building during October. The breakdown of power consumption is shown on the left y-axis; the outside temperature on the right y-axis.

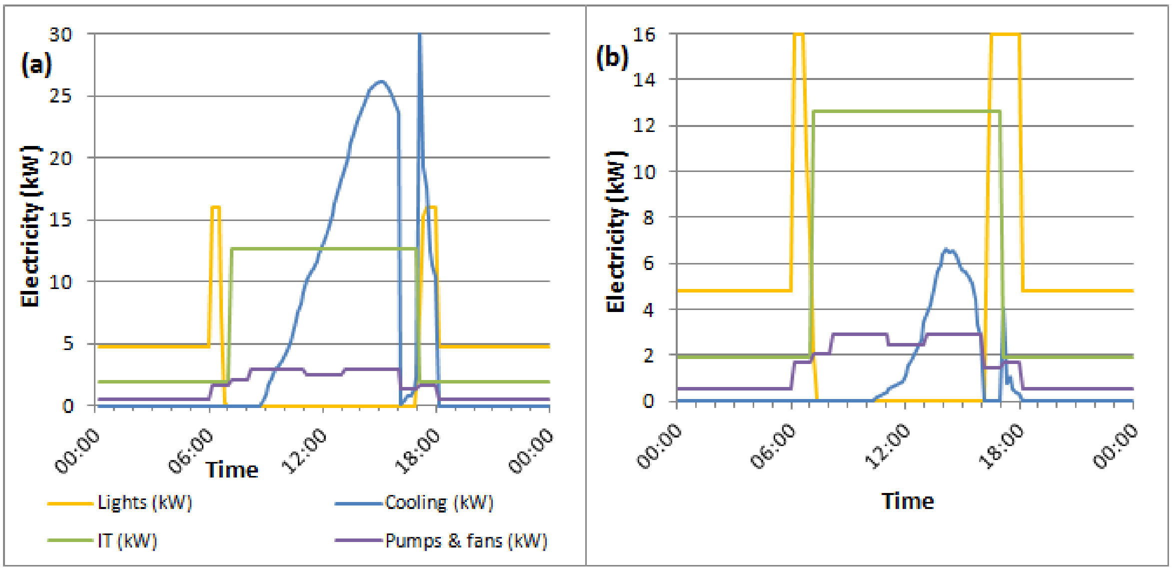


Figure 54 Electricity consumption in the load shift scenario for a Type 1, 1990s gas heated building on (a) 1st October and (b) 22nd October

Figure 54 illustrates the electricity consumption on two days in October when cooling was required. In both cases, cooling and HVAC auxiliary systems reduced demand at the start of the load shift period. In figure 54 (a) the cooling was reduced initially to zero but then increased to a low level (below 5 kW). The lighting and IT remained constant during this time. Figure 54 (b) shows a reduction in cooling during the load shift period which coincided with an increase in lighting demand, due to the falling daylight levels. The lighting load was greater than the cooling load and this resulted in a net increase in electrical power.

During the load shift periods, the heating and cooling were turned down but on some days there was little or no reduction. Figure 55 shows the breakdown of electricity by end use for a type 1, 1970s building with electric heating. This building has high heat loss due to low levels of insulation and from being narrow plan. During the period of 8th to 12th April, there was a small demand for cooling (on Wednesday 10th April to Friday 12th April). Shifting this demand resulted in small load reduction (3 to 20 kW). The electric lighting increases around the time of the load shift period, which sometimes results in a net increase in load.

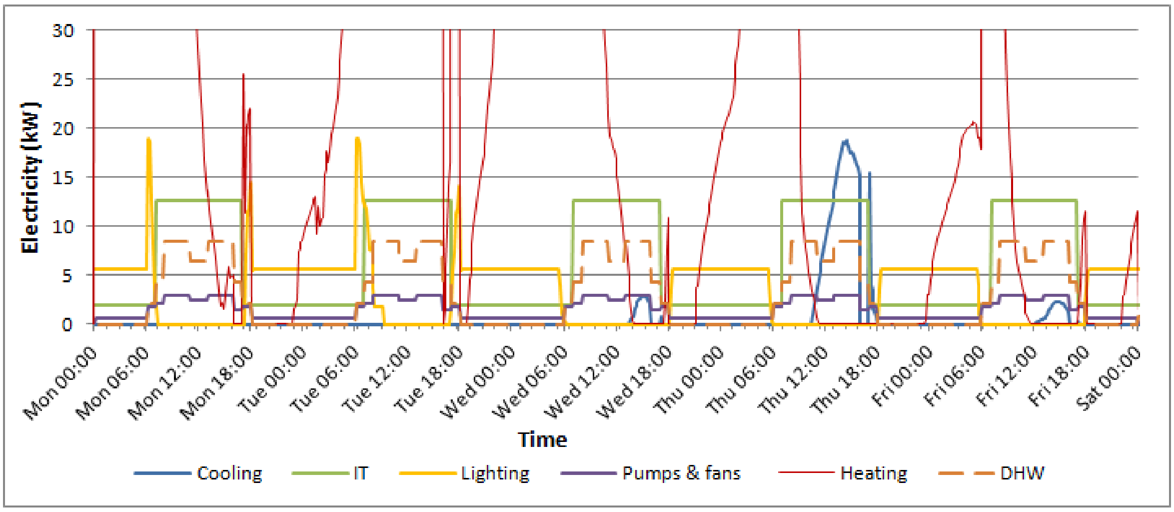


Figure 55 Breakdown of electricity for a Type 1, 1970s building with electric heating in the *load shift* scenario for 8th to 12th April

Figure 56 shows the breakdown of electrical load for the same building for Tuesday 9th April. The load shift period is shown as 16:00 to 17:00 because EnergyPlus adjusts for British Summer Time (BST), by recording the results against GMT (section 6.3.6). The heating demand dropped to zero at the start of the load shift period but by 16:20 was at 4 kW and increased to 16 kW by 17:00. The low outside temperature (below 6°C) was driving the heat demand. The building lost heat at a high rate to the environment through the poorly insulated fabric. The lighting demand rises above zero just before 17:00, resulting in a net increase in demand.

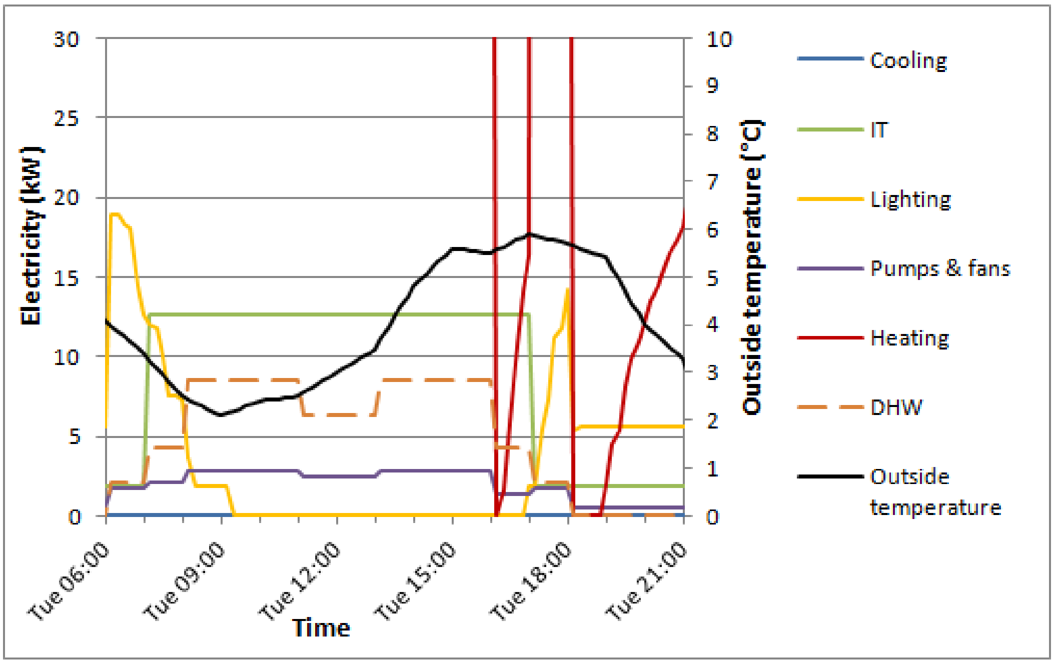


Figure 56 Breakdown of electricity in a Type 1, 1970s building with electric heating in the *load shift* scenario for 9th April. The end uses of electricity (coloured lines) are shown against the left Y-axis; the outside temperature (black line) against the right Y-axis. The load shift period is shown as 16:00 to 17:00 because of the adjustment for BST.

7.2.2 Single building: temperature

This section considers the mean internal building temperatures for each model case as an indicator of occupant comfort. The temperatures of individual zones of a building are illustrated in figure 49 for a single simulation. This shows three areas of office space (zone 1a on each floor) and the building mean. During this cold period, the mean temperature was lower than the temperatures of individual office zones. The common areas had a lower mean setpoint than the office areas (21°C compared with 21°C to 23°C). During load shift periods, the heating in common areas was setback to a lower level than office areas (16°C instead of 19°C).

Each building case was simulated ten times with heating and cooling setpoints selected from the ranges: 21°C to 23°C and 22°C to 24°C respectively (table 28 in section 6.3.4). During load shift periods, heating was setback to 19°C and cooling to 26°C in office areas. In common areas, the setback temperatures were 16°C and 28°C. For each simulation, the mean building temperature, weighted by floor area was calculated (section 6.3.8). An example of this is figure 57 which shows the mean internal temperature for each of the ten simulations. This is for a type 2, 1970s building with gas heating and load shift each weekday. The building temperature for the ten simulations (in colour) has a range of values from 21°C to 24°C during working hours (apart from the load shift periods). During load shift periods, the mean temperature dropped to 18°C for 29 hours / year (table 55).

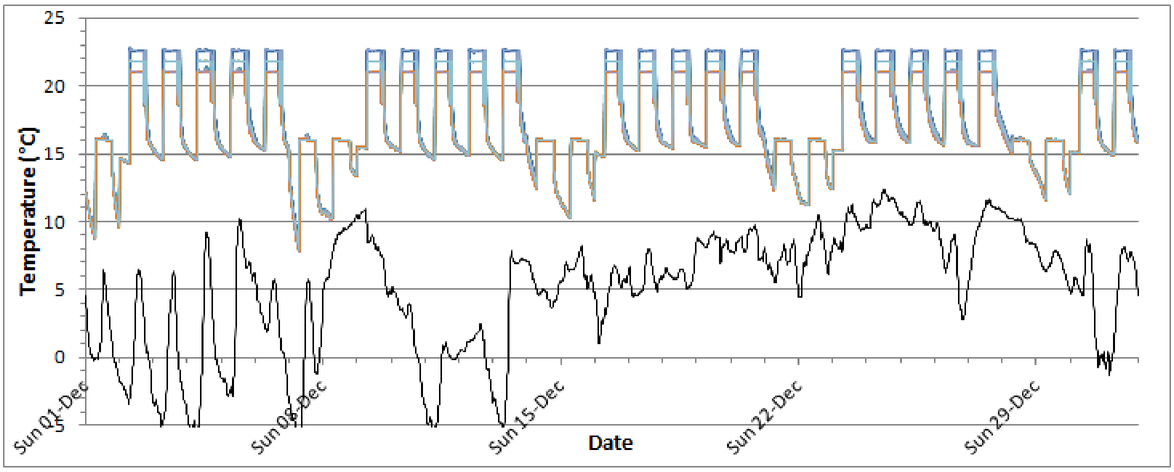


Figure 57 Mean building temperature for a type 2, 1970s building with gas heating, in the load shift scenario. Ten simulations were carried out (represented by the coloured lines), each with a different set of parameter values. The black line represents the external temperature.

The mean building temperatures during *occupied hours* for BaU and load shift scenarios were compared. *Occupied hours* were defined as 08:00 to 18:00 on all weekdays (2610 hours / year) (section 6.3.4). The mean building temperature was calculated across all ten simulations and the number of hours at each temperature during the occupied period was calculated. In the BaU scenario, the mean internal temperature was between 21°C and 24°C for all occupied hours, for all model cases (see table 55). In the load shift scenario, all occupied hours were between 18°C and 27°C. In no model case did the temperature exceed 27°C in either load shift or BaU scenarios. This complied with CIBSE's Benchmark that '*the internal operative temperature should not exceed 25 °C for more than 5% of occupied hours and 28 °C for more than 1% of occupied hours*' (CIBSE 2015). The fabric standard had a greater effect on the temperature than whether the building was narrow plan (types 1 and 2) or deep plan (types 3 and 4). The model cases with the highest number of occupied hours below 21°C were those with poor insulation (1970s fabric). The cases with the highest number of occupied hours above 25°C were the most insulated ones (1990s fabric). The model cases with the greatest risk of over-heating was type 1, 1990 build with either gas or electric heating, with 3% of occupied hours (77 hours) above 25°C.

Table 55 The distribution of mean temperatures during *occupied hours* for each model case in BaU and load shift scenarios. All temperatures were recorded within the range below.

	BaU (hours)	**Load shift** (hours within specified range)					Built form	Age band	Heating
Case	21 to 24 °C	18 to 19 °C	19 to 21 °C	21 to 24 °C	24 to 26 °C	26 to 27 °C			
1	2610	27.2	108.3	2409.2	55.2	10.2	2	1970	Electric
2	2610	28.7	107.0	2409.0	55.2	10.2	2	1970	Gas
3	2610	7.2	110.3	2423.2	59.0	10.3	2	1980	Electric
4	2610	7.2	110.2	2423.3	58.8	10.5	2	1980	Gas
5	2610	0.0	57.7	2445.8	82.0	24.5	2	1990	Electric
6	2610	0.0	57.7	2445.8	82.0	24.5	2	1990	Gas
7	2610	40.3	97.0	2405.3	50.3	17.0	1	1970	Electric
8	2610	40.2	96.7	2405.5	50.5	17.2	1	1970	Gas
9	2610	14.7	105.3	2418.0	52.5	19.5	1	1980	Electric
10	2610	14.7	105.3	2418.0	52.5	19.5	1	1980	Gas
11	2610	0.0	60.0	2437.2	78.2	34.7	1	1990	Electric
12	2610	0.0	60.0	2437.2	78.2	34.7	1	1990	Gas
13	2610	38.0	98.8	2407.0	49.0	17.2	3	1970	Electric
14	2610	37.5	98.8	2406.8	49.7	17.2	3	1970	Gas
15	2610	13.2	102.5	2421.8	53.5	19.0	3	1980	Electric
16	2610	13.2	102.5	2421.7	53.7	19.0	3	1980	Gas
17	2610	0.0	56.5	2441.0	79.3	33.2	3	1990	Electric
18	2610	0.0	56.5	2441.0	79.3	33.2	3	1990	Gas
19	2610	27.7	105.5	2412.5	55.7	8.7	4	1970	Electric
20	2610	27.3	105.5	2412.7	55.7	8.8	4	1970	Gas
21	2610	7.3	102.0	2431.8	59.5	9.3	4	1980	Electric
22	2610	7.3	101.8	2432.0	59.5	9.3	4	1980	Gas
23	2610	0.0	43.8	2457.8	87.8	20.5	4	1990	electric
24	2610	0.0	43.8	2457.8	87.8	20.5	4	1990	gas

The model cases with the longest period of low temperatures were type 1, 1970 build with either type of heating. In these cases, the temperature was below 19°C for 1.5% of occupied hours (40 hours). The temperature was above 18°C for all occupied hours in all model cases.

Figure 58 and figure 59 show the duration at each temperature for four example cases during occupied hours. Figure 58 relates to a narrow plan, open plan building (type 1). Figure 58(a) is for a 1970s building with electric heating; figure 58(b) relates to a 1990s building with gas heating. The heating system type did not affect the duration at these temperatures (table 55). The BaU scenario (in blue) was compared with the load shift scenario (in red). In the BaU scenario, the mean temperature was constrained within the 21°C to 24°C range for all occupied hours. In the load shift scenario, the temperatures of these buildings went outside these thresholds for a few hours. The temperature in the 1970s building was below 21°C for 137 hours, compared with 60 hours for the 1990s building. This was due to the poorer insulation in the older building. The opposite effect was observed at higher temperatures due to lower heat loss from a well insulated building. In the 1970s building, the temperature was between 26.0°C and 26.9°C for 17 hours, compared with 35 hours for the 1990s building.

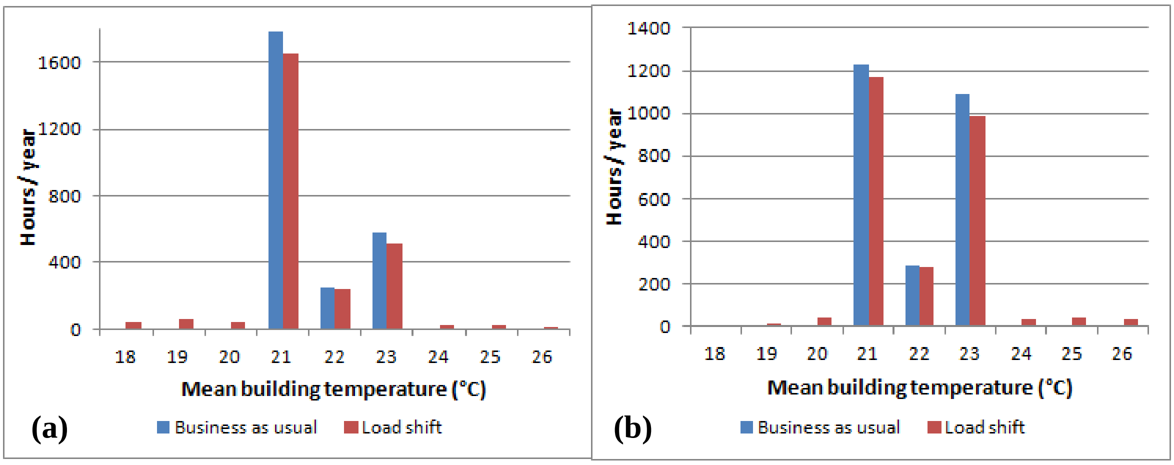


Figure 58 Comparison of mean temperatures during occupied hours for type 1 buildings (a) with 1970s fabric and electric heating (b) 1990s fabric and gas heating

Figure 59 relates to a deep plan, cellular building (type 4). Figure 59(a) is for a 1970s building with gas heating; figure 58(b) relates to a 1990s building with electric heating. In the BaU scenario (in blue), the mean temperature was between 21°C and 24°C for all occupied hours as specified. In the load shift scenario, the temperature in the 1970s building was below 21°C for 133 hours, compared with 44 hours for the 1990s building. This was due to the poorer insulation in the older building. In the 1970s building, the temperature was between 26.0°C and 26.9°C for 9 hours, compared with 20.5 hours for the 1990s building.

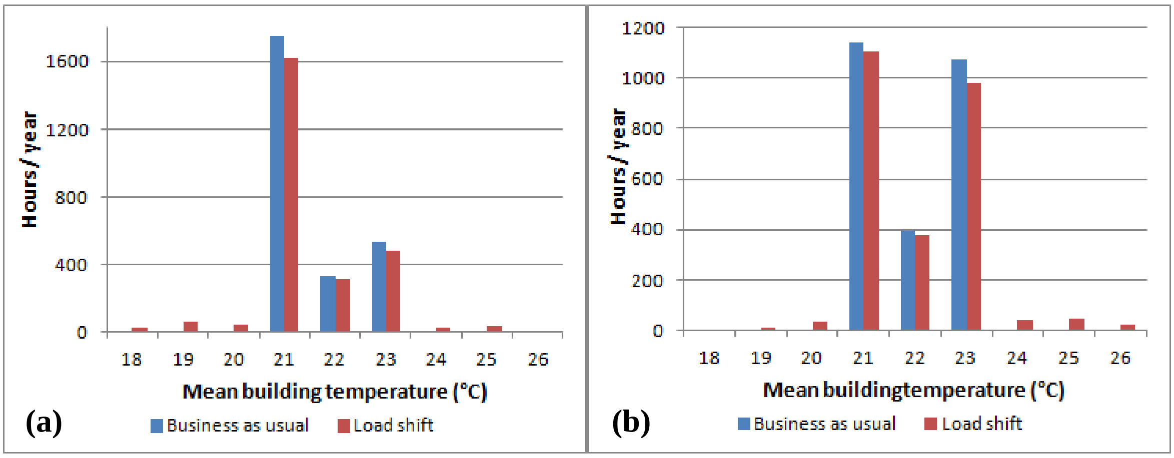


Figure 59 Comparison of mean temperatures during occupied hours for type 4 buildings (a) with 1970s fabric and gas heating (b) 1990s fabric and electric heating

These simulations represent a DSM period each weekday (section 6.3.8). This is more frequent than 40 or 50 times / year from a DNO or System Operator DSM service. If load shifting was restricted to this frequency, this would reduce the number of hours at the highest and lowest temperatures.

7.2.3 Single building: load-shift

The '*power difference*' between each load shift case and the corresponding business as usual (BaU) case was determined. Each building was simulated with the heating and cooling setback from 17:00 to 18:00 each working day (section 6.3.8). Ten simulations were carried out, each with a random selection of values for heating and cooling setpoint and building orientation (using values in table 31, in section 6.3.5). The power difference was calculated for load shift period. This was the difference between the load at 17:00 (the baseline load) and the load at each timestep (equation 12 in section 6.3.8). This is illustrated in figure 60. The 95th percentile of the power difference at the final timestep (18:00) for all days in the month (or season) gave the indicative DSM potential. The use of 95th percentiles recognised the requirements of National Grid and DNOs for a guaranteed service (sections 4.4.1 and 4.4.3). The variation in the calculated load shift was due to the weather and the different parameter values (heating and cooling setpoint and building orientation).

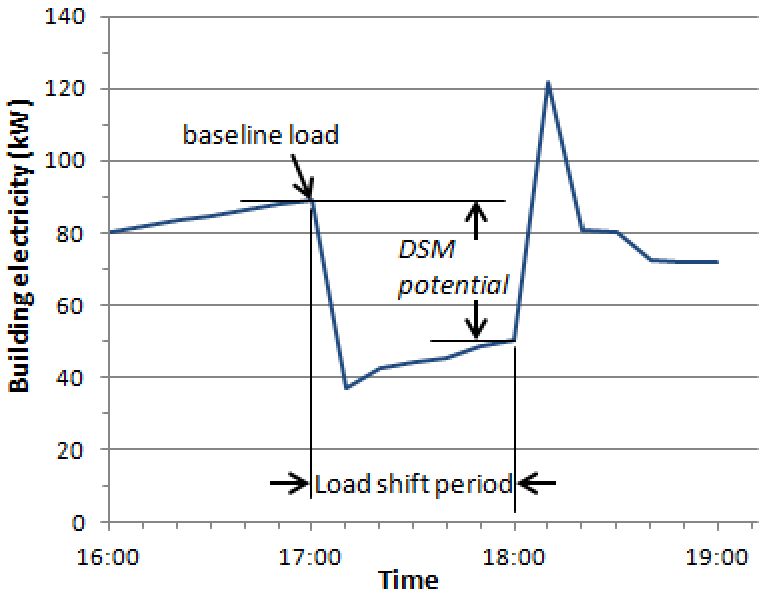


Figure 60 Calculation of electrical load shift due to heating and cooling setback, illustrated for a type 1, 1970s building with electric heating

Figure 61 and figure 62 show the *power difference* at 18:00 for each simulation case, for each month. A negative value means that the building electrical load was less at 18:00 compared with 17:00 and therefore potential for DSM. A positive value shows that the building electrical load increased during the load shift hour, compared with the baseline. Figure 53 and figure 54 show that the electrical load may reduce for part of an hour followed by an increase due to lighting or cooling demand. Figure 61 and figure 62 show 95th percentiles of load reduction which are intended to ensure that DNO and System Operator requirements for availability are satisfied (section 6.3.8).

For the gas heated cases, figure 61, the largest load reduction was during the summer and for the newest (1990s) buildings. This was due to higher cooling demand in better insulated buildings. The 1970s and 1980s buildings show load reduction only in July and none in August. Across all building types and age bands there was similar (but small) load reduction in January, November and December. This was due to the load reduction from HVAC pumps. There was a net increase in electrical demand for all cases during February, March, April, September and October. Comparing the built form types, the load reductions for a particular age band were similar. Types 1 and 3 (both open plan) often have greater load reduction than the cellular types (2 and 4).

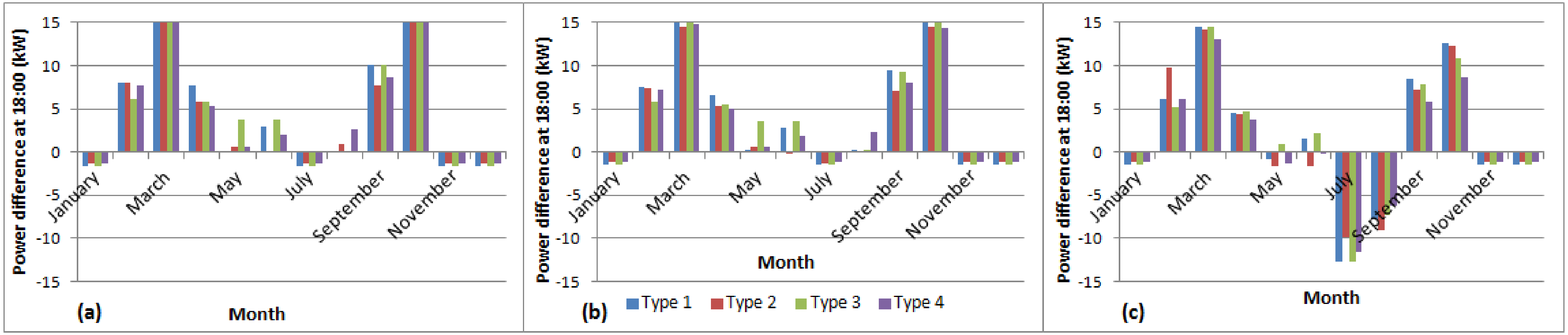


Figure 61 95th percentile of change in electrical load at 18:00, compared with 17:00, for *gas* heated cases (a) 1970s, (b) 1980s, (c) 1990s

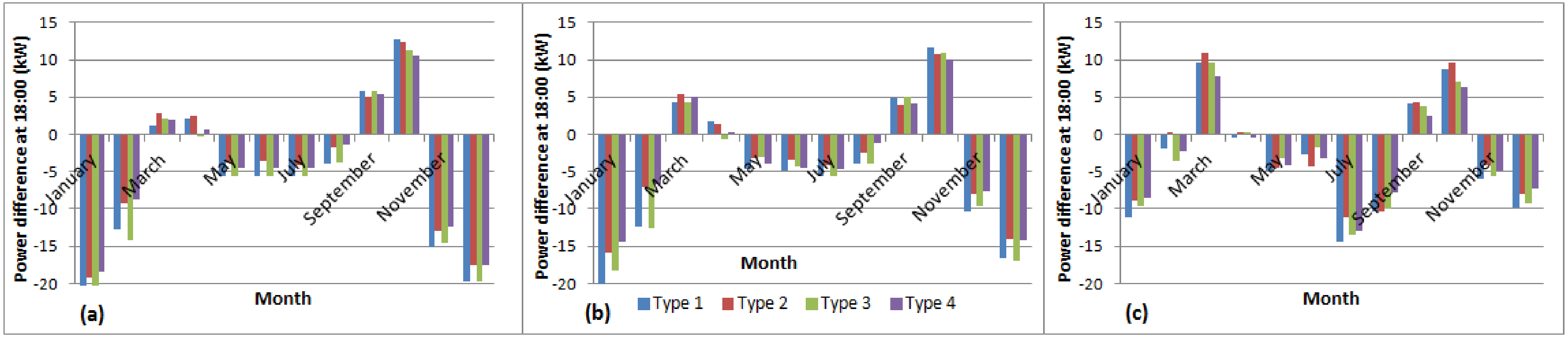


Figure 62 95th percentile of change in electrical load at 18:00, compared with 17:00, for *electric* heated cases (a) 1970s, (b) 1980s, (c) 1990s

Considering the electrically heated cases (figure 62), the greatest load reductions are in the 1970s buildings in the cold months (January, February, November and December). Negative values of *power difference* mean load reduction and potential for DSM. The better insulated buildings still have a reduction in load during these months but it is not as great due to the reduced heating demand. All age bands demonstrated load reduction during the warmer months (May to August). This was greater in the better insulated cases and was caused by increased cooling demand. March, April, September and October do not show a demand reduction across any of these cases. This was due to a low requirement for heating and cooling due to the milder weather, leading to little possibility for a reduction in this load. Open plan types 1 and 3 show slightly greater reduction than cellular types 2 and 4.

During October, a net increase in electrical load was observed in the plots of change in electrical load (figure 61 and figure 62). With the gas heated cases, reduction in electrical load was possible from cooling and HVAC auxiliary systems. During October, cooling was required on a small number of days, related to the outside temperature, figure 53. The better insulated, 1990s buildings required more cooling than the 1970s buildings, which resulted in more days when the building load was reduced in response to a DSM request.

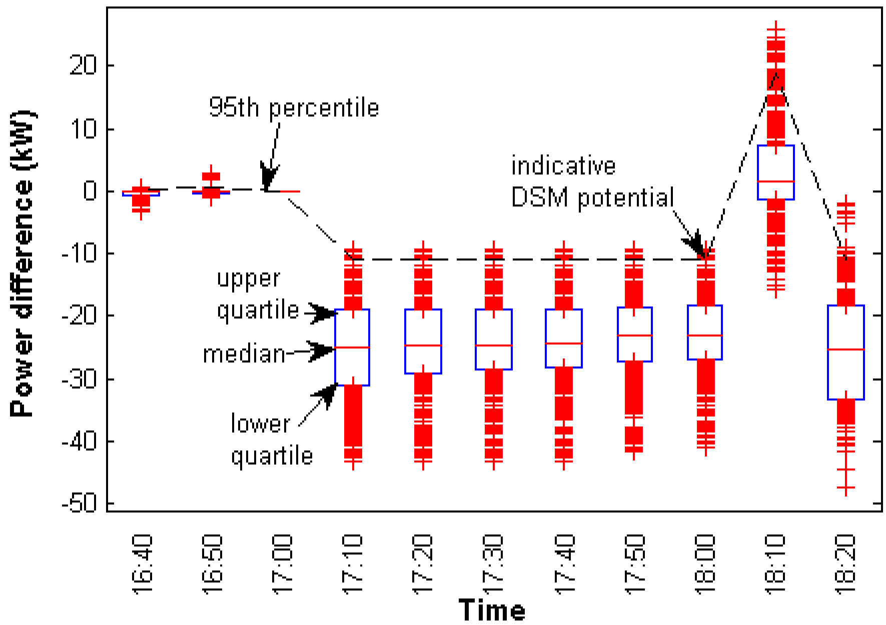


Figure 63 Power difference for a type 3, 1980s electric heated building for 27th October to 2nd February 2015 (season 5). '*Power difference*' is the building electrical power at any timestep minus the power at the timestep prior to the start of the DSM period (17:00).

The change in electrical load for each simulated building (figure 61 and figure 62) was grouped by 'season' so that these could be compared with the requirements of National Grid's STOR service. Figure 63 shows the power difference for one STOR season as a boxplot. The simulation period was 27th October to 2nd February 2015 (season 5), which consisted of 68 working days. Ten simulations were carried out. For each timestep, a box of the data was plotted, which shows median, lower and upper quartiles. The 95th percentile was added (the broken black line in figure 63) to indicate the threshold for a STOR service. The 95th percentile at the last timestep during the load shift period (18:00) was taken as the DSM potential for one hour. Table 56 gives the DSM potential for each case and each STOR season. The effect of grouping these data into longer periods is to show a smaller load reduction. For example, figure 61 (c) shows a reduction in load (a negative value) for gas heated, type 2, 1990s buildings during May to August. The reduction in May and June is below 5 kW but close to 10 kW in July and August. In table 56, these data are aggregated in 'season 2' (28th April to 18th August). This gives a mean value for the entire season of -2.17 kW (a reduction of 2.17 kW). Figure 61 and figure 62 show almost no load reduction during April and none during, September and October for any building case. This is reflected in the reductions in season 1 (1st to 28th April) of no more than -1.74 kW (case 17) and season 4 (22nd September to 27th October). Season 4 has no load reduction for any case. The positive values represent net load increase.

Table 56 95th percentile of load reduction (kW)

	1st to 28th April	28th April to 18th August	18th August to 22nd Sept	22nd Sept to 27th Oct	27th Oct to 2nd Feb	2nd Feb to 1st April			
Case	Season 1	Season 2	Season 3	Season 4	Season 5	Season 6	Built form type	Age band	Heating
1	2.988	-3.600	2.629	12.155	-14.333	1.956	2	1970	Electric
2	5.717	0.628	6.871	14.749	-1.318	14.814	2	1970	Gas
3	1.823	-3.660	2.619	10.546	-9.452	3.258	2	1980	Electric
4	5.318	0.171	5.975	13.655	-1.176	13.716	2	1980	Gas
5	0.302	-4.859	1.980	8.282	-4.569	9.668	2	1990	Electric
6	4.702	-2.170	4.812	10.762	-1.152	13.868	2	1990	Gas
7	2.158	-5.691	4.123	11.368	-16.551	-0.349	1	1970	Electric
8	6.427	1.958	9.805	17.192	-1.693	16.279	1	1970	Gas
9	1.760	-5.691	4.323	10.985	-11.636	2.627	1	1980	Electric
10	6.025	1.900	8.891	15.873	-1.470	15.119	1	1980	Gas
11	-0.885	-4.913	-0.134	8.383	-6.246	7.718	1	1990	Electric
12	3.893	-1.152	3.907	12.423	-1.433	13.611	1	1990	Gas
13	0.425	-5.647	4.159	11.129	-15.799	0.013	3	1970	Electric
14	5.566	3.755	9.728	15.238	-1.679	16.144	3	1970	Gas
15	-0.631	-5.647	4.283	9.969	-10.886	2.713	3	1980	Electric
16	5.230	3.558	8.823	14.158	-1.458	14.994	3	1980	Gas
17	-1.743	-3.599	-0.136	6.618	-6.205	7.706	3	1990	Electric
18	2.480	0.111	3.810	10.321	-1.421	13.457	3	1990	Gas
19	0.783	-4.481	2.904	10.067	-14.000	0.902	4	1970	Electric
20	5.302	1.580	7.070	15.903	-1.328	13.102	4	1970	Gas
21	0.529	-4.481	2.126	9.909	-9.115	2.194	4	1980	Electric
22	4.937	1.020	6.570	14.161	-1.182	12.138	4	1980	Gas
23	-1.466	-4.573	0.737	6.244	-5.059	6.271	4	1990	electric
24	3.468	-1.551	3.638	8.652	-1.158	10.696	4	1990	gas

The difference in electrical power (load-shift minus baseline) was calculated for each timestep, for each iteration and analysed by STOR season (section 6.3.8). The median and inter-quartile range (IQR) of the power difference were plotted for the load-shift period. Figure 64 is an example of this for a type 2 building, 1990s fabric with gas heating and electric cooling. Each plot represents a STOR season. The broken black line is the 95th percentile of power reduction.

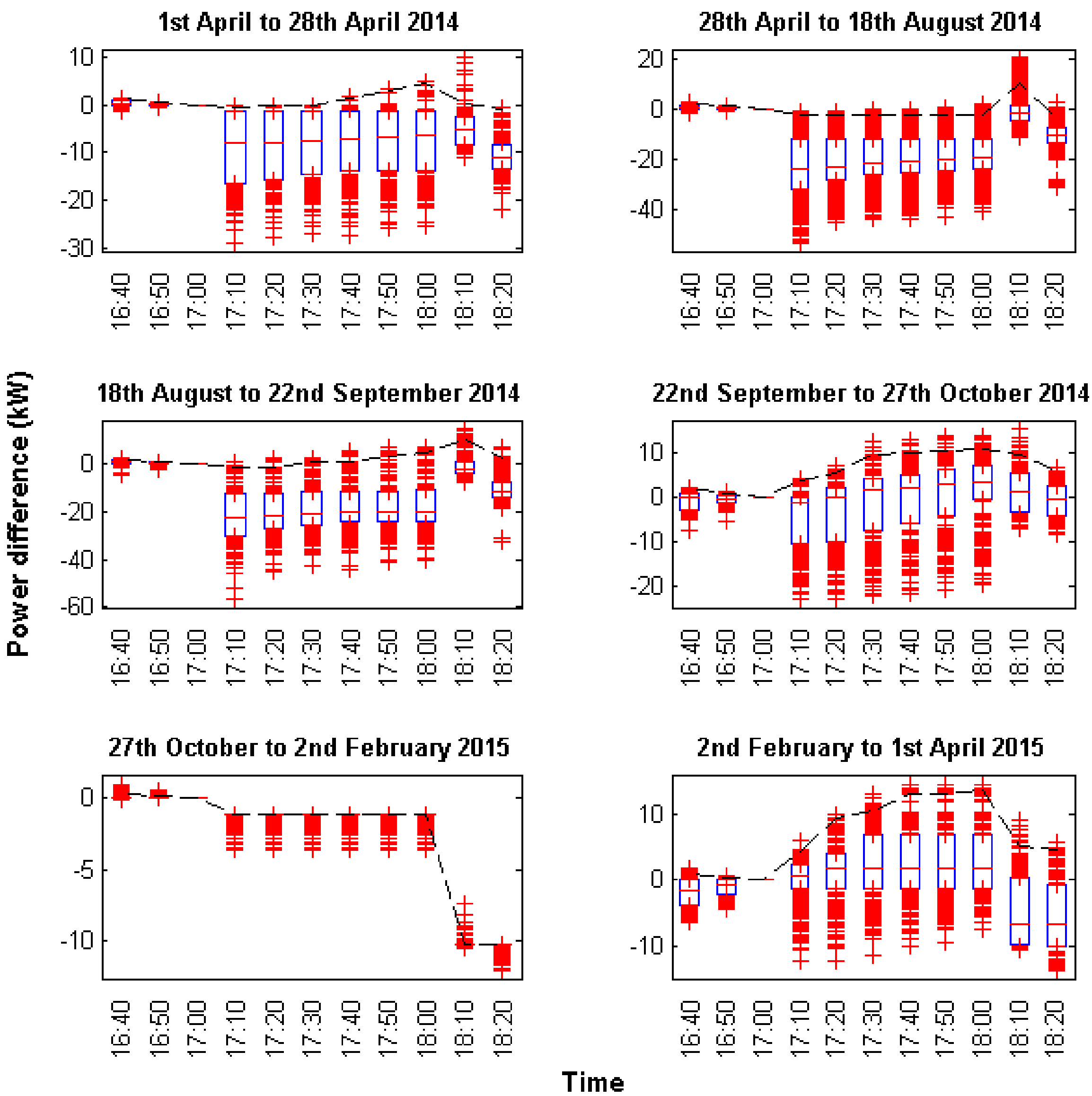


Figure 64 Power difference for a type 2, 1990s building with gas heating and electric cooling

The 95th percentile of the power difference during the load-shift period was calculated for each season. The maximum (least negative value) for each load-shift period was used to indicate the potential demand reduction for one hour.

7.2.4 Analysis Case Studies

7.2.4.1 Duration of Load shift period

If the load-shift period is less than one hour, is a larger reduction possible?

The model developed in this research examined the reduction in building electrical loads from turning down the heating and cooling for one hour. However some cooling and heating were required in order to maintain the load shift setback thresholds of 19°C and 26°C (section 6.3.4). This is seen to reduce the electrical load for up to 20 minutes before it increases due to the demand for cooling or heating to meet the setback levels. The analysis below evaluates the profile of the power difference during the one hour load shift period to see if a load reduction is possible for less than one hour.

The 95th percentile of power difference of each timestep during the load-shift period was calculated (PDi), using equation 12. Values of PDi for successive timesteps were compared for each model case, in order to identify any variation. The variation in PDi during the load-shift period depends on the heating system type, the level of insulation, the built form and the time of year. This is illustrated by examples for a narrow plan, 1970s building with electric heating, figure 65 and a deep plan, 1990s building with gas heating, figure 66.

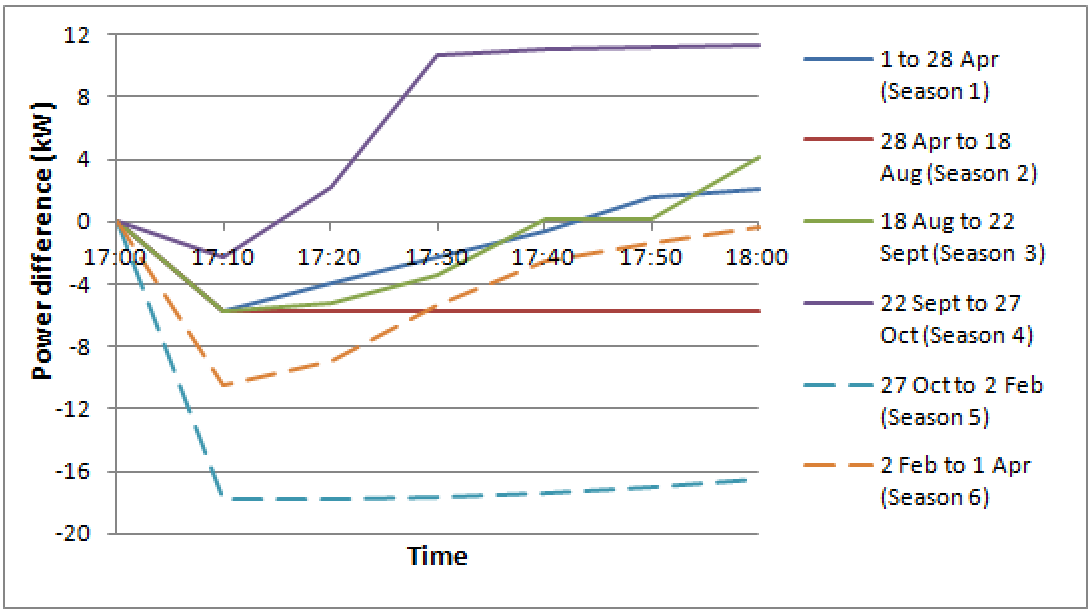


Figure 65 Power difference during a load shift period for a Type 1 1970s building with electric heating. Each line shows the 95th percentile of power difference for a STOR season.

The electrically heated building (referred to in figure 65) shows a power reduction for 10 minutes during season 6 (2nd February to 1st April 2015) followed by power increase. The heating or cooling may be turned down for 10 minutes but is required again in order to maintain the temperature within the limits of 19°C and 26°C.

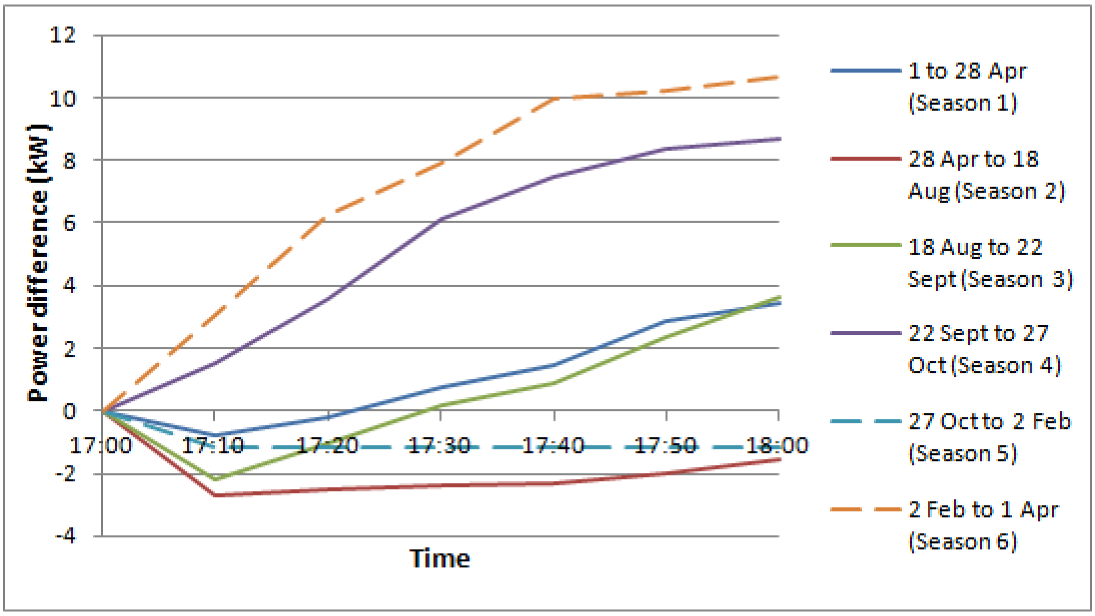


Figure 66 Power difference during a load shift period for a Type 4 1990s building with gas heating. Each line shows the 95th percentile of power difference for a STOR season.

Figure 66 shows the power difference for each STOR season for a 1990s, type 4 (deep plan) building with gas heating. This is the reduction in electrical power compared with the demand at 17:00. During the period of 28th April to 18th August, the electrical load may be reduced by turning down the cooling. However this reduction is smaller than for the type 1 building in figure 65 and is not constant for one hour. Due to the plan depth and being well insulated the heat loss is lower and some cooling is required. This causes the power difference to become smaller during the hour. A small and constant reduction is observed during season 5 (27th October to 2nd February). This is due to the pump power being reduced during load shift periods. At other times of year, the power difference is positive for the whole hour or becomes positive after 20 to 30 minutes. A positive value of power difference indicates a net increase in electrical load. At these times of year, the cooling demand is low, so the scope for reduction is small. The demand for artificial lighting was set to change in response to daylight (section 6.3.4). On some days, the demand for lighting increased during the load shift period and more than negated any power reduction from cooling, as was seen in figure 54(b).

7.2.4.2 How much of the building load is flexible

The contribution of ‘flexible’ electrical loads was determined in order to identify how the potential for DSM services would vary by season. For gas heated cases, the flexible loads were cooling and HVAC pumps. For electrically heated cases, heating was also included. The ‘flexible load’ was the electricity consumed by the named end uses at all times of day. The size of the flexible electrical load was broken down by NG STOR season in order to determine the capacity to deliver this service.

This analysis was carried out on building type 2 (narrow plan, cellular), as the most frequently occurring built form type (section 3.3.1). Simulations were carried out for this building with 1970s, 1980s and 1990s fabric, with gas heating and with electric heating. This was analysed for summer and winter periods, defined by two STOR seasons: 28th April to 18th August 2014 (season 2) and 27th October to 2nd February 2015 (season 5). The electricity consumption was calculated for this period and scaled to one year so that it could be compared with annual electricity data. The buildings were simulated for business as usual (no load shifting). The heating and cooling setpoints were: 22°C and 23°C respectively.

The flexible load during season 2 (28th April to 18th August 2014) was similar for gas and electrically heated cases (figure 67). The flexible load with the gas heated cases was 41% to 53% of the total electrical load; with the electrically heated cases, this was 37% to 43%. The gas heated, 1990s building case had the largest flexible load. This is an example of a well insulated building requiring extra cooling when the external temperature is high. The higher electricity consumption in the gas heated case, compared with the electrically heated case is due to the lower cooling CoP (section 6.3.3.3).

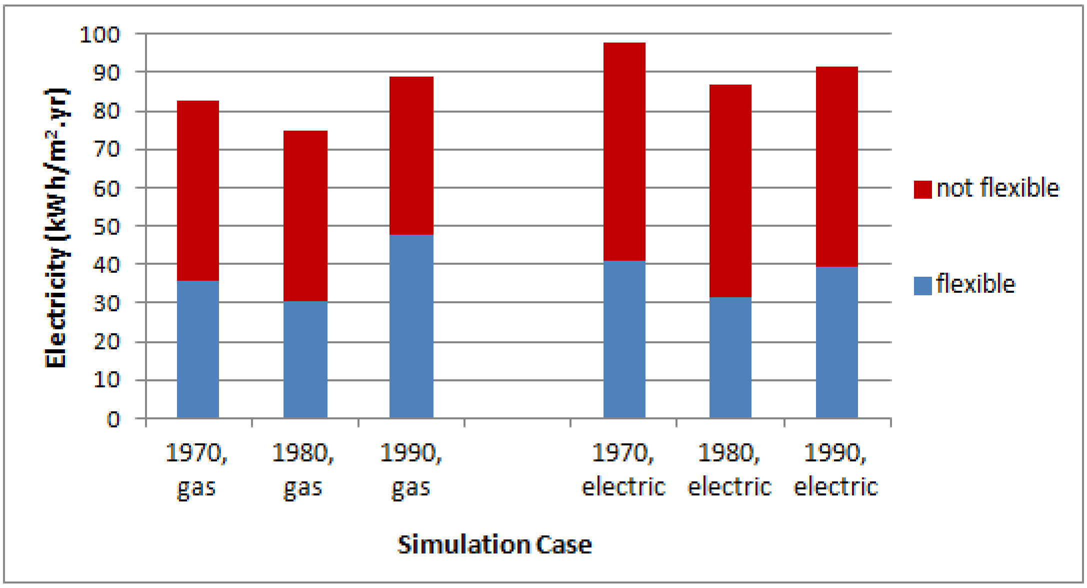


Figure 67 Contribution of flexible and non-flexible electrical loads for a type 2 building for the period: 28th April to 18th August 2014 (season 2) and scaled to one year. From left to right: simulations for 1970s, 1980s, 1990s fabric (gas heated and electric heated). The simulation was for business as usual with heating setpoint of 22°C and cooling at 23°C.

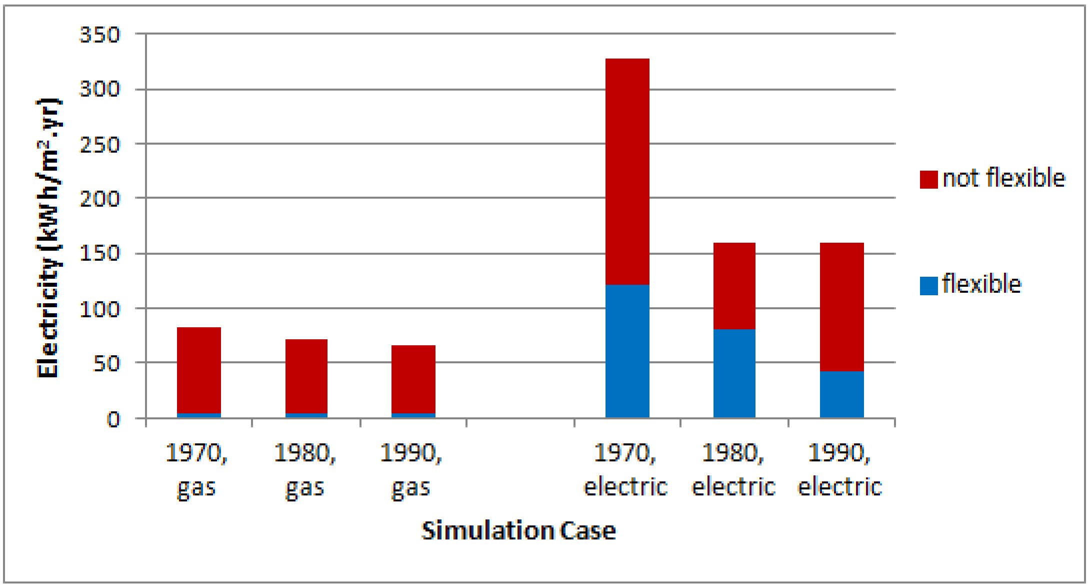


Figure 68 Contribution of flexible and non-flexible electrical loads for a type 2 building for the period: 27th October to 2nd February 2015 (season 5), and scaled to one year. From left to right: simulations for 1970s, 1980s, 1990s fabric (gas heated and electric heated). This was for the BaU scenario with heating setpoint at 22°C and cooling at 23°C.

The flexible load during season 5 (27th October to 2nd February 2015) was significantly lower for cases heated by gas compared with electricity. With the gas heated cases, the flexible load amounted to 5% to 7% of the total electrical load; with the electrically heated cases, this was 27% to 51%. With the gas heated cases, the flexible load consisted almost entirely of HVAC pumps since the cooling energy consumption was small. For the electrically heated cases during season 5, the 1970s building had the largest flexible load (in kWh). This was due to high heating demand resulting from the heat loss through the building fabric. The better insulated 1990s building consumed less electricity for heating which resulted in less flexible load.

These results suggest that gas heated buildings have little flexible load to contribute to DSM when the demand for these services is greatest. The contribution to DSM from HVAC pumps is tiny during STOR season 5 (27th October to 2nd February 2015). However some buildings will contribute flexibility from other end uses such as hot water and refrigeration. With electrically heated cases, if the building fabric is improved through insulation this is likely to reduce the flexible load in the cold months and the DSM opportunity. During STOR season 2 (28th April to 18th August 2014), the best insulated buildings had the lowest heat demand and highest demand for cooling. This resulted in similar flexible load.

7.2.4.3 Comparison of load shift with external temperature

The relationship between the shiftable load and the external temperature was investigated. Since the load being ‘flexed’ was heating and cooling, it was expected that the load reduction would be greater on days with more cooling (and heating, where this was electric). A type 2, 1990s gas heated building was simulated for one year in the load shift scenario (heating and cooling setback from17:00 to 18:00 each weekday). This building case represented the most popular built form type with the more popular HVAC type and recent construction. The power difference was evaluated for STOR season 2 (28th April to 18th August) as this period had the greatest demand for cooling. For each load shift period, the final timestep (18:00) was taken as the indicator for the potential load reduction. This was plotted in figure 69 (red line, left Y-axis). The mean external temperature for each calendar day was plotted in black (right Y-axis). Figure 69 appears to show that on warmer days, with a higher demand for cooling, there is a greater electrical load reduction when the HVAC is setback for one hour. The two data sets (power difference at 18:00 and mean external temperature) have a correlation coefficient of 0.813. This shows a moderately strong correlation for this specific period and for this particular model case.

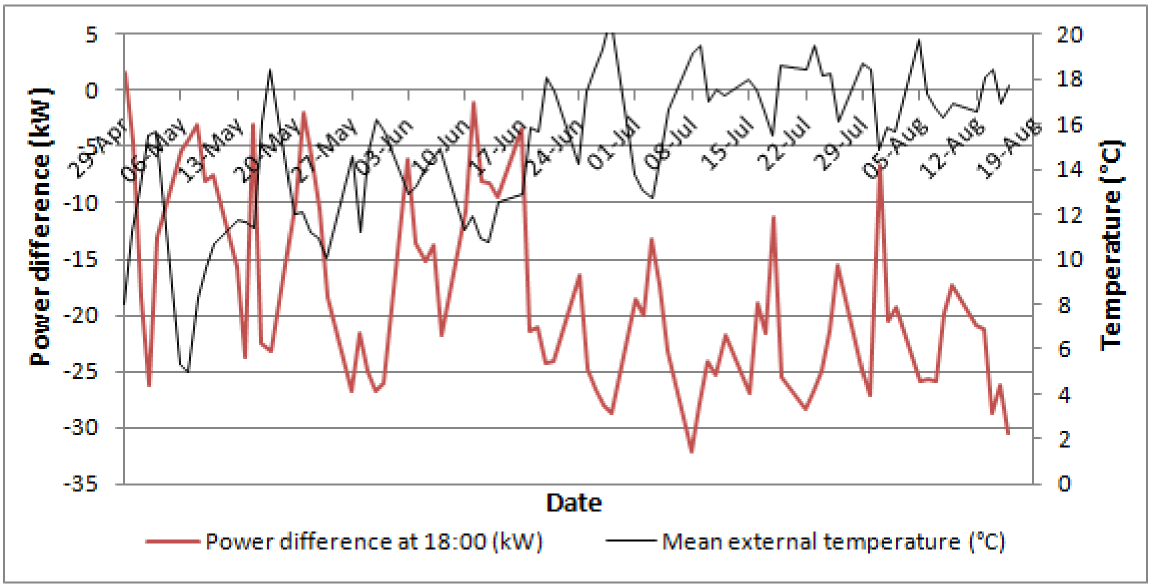


Figure 69 Power Difference at 18:00 (left Y-axis) and daily mean external temperature (right Y-axis) for a Type 2, 1990s gas heated building from 29th April to 16th August.

7.2.5 Comparison of cases with measured building data

Data from the single building simulations in the BaU scenario, were compared with electricity data from buildings in Reading. Reading Library was compared with a type 3, 1980s, gas heated building (described in section 6.3.9). The electricity consumption data for Reading Library consisted of meter readings in kWh for each half-hour settlement period from 1st January to 31st December 2014. Reading Library has both natural ventilation through windows and electrically driven ventilation (section 6.3.9). In contrast, the model type 3 building relies entirely on the HVAC system for ventilation and cooling.

The model and library data were disaggregated by NG STOR season. Weekdays were removed due to office space having low occupancy at weekends in the model. Each data sets was normalised by the floor area, to give electricity consumption in kWh/m^2 for each half-hour settlement period (SP). The median electricity consumption for the weekdays in each STOR season was calculated.

Figure 70 compares the median electricity consumption from the summer and the winter. Figure 70(a) covers 28th April to 18th August 2014 (season 2); (b)1st January to 2nd February and 27th October to 31st December 2014 (season 5).

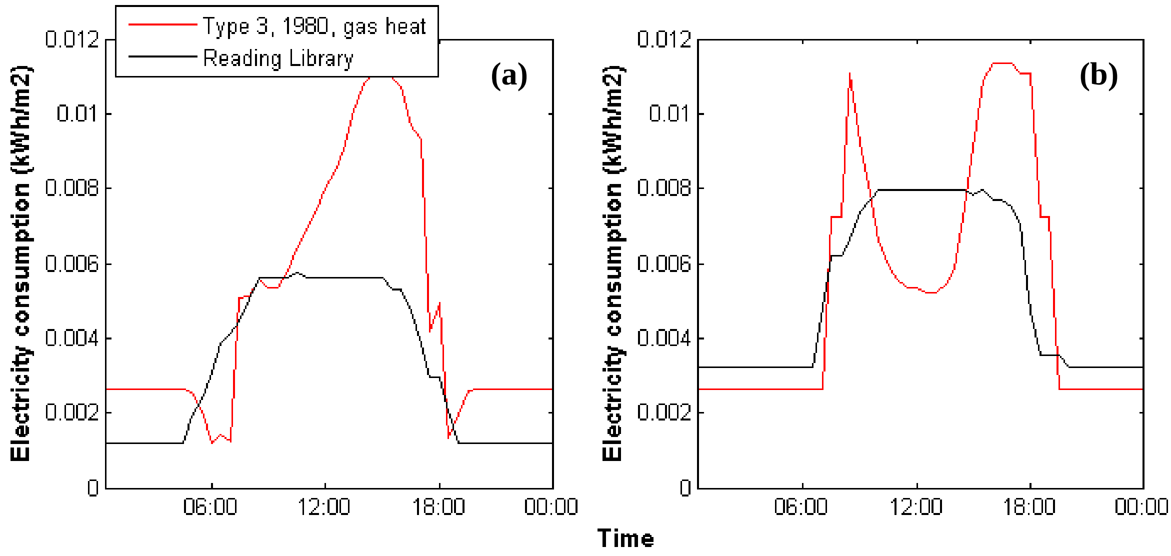


Figure 70 Comparison of median electricity consumption for Reading Library (black lines) with model type 3, 1980s build and gas heating (red lines) for (a) 28th April to 18th August 2014 and (b) 1st January to 2nd February and 27th October to 31st December 2014

Figure 70a relates to a period with high outdoor temperatures during which the internal building temperature increased. In the model case, cooling was supplied to hold the temperature within the comfort band. This resulted in the steep rise in electricity demand (red line). The electricity demand in the library (black line in figure 70a) remained almost flat during the day. This building has air-cooled chillers and fan coil units supplying fresh air. According to the Facilities Manager at Reading Borough Council, the chillers '*have not run properly for some time*' and most of the fan coil units have failed (Attree 2016, personal communication). Some windows can be opened on the ground, first and second floors and these provide ventilation and cooling. The third floor is supplied entirely by natural ventilation.

During the winter, figure 70b, the lighting in the modelled building was significant and depended on the daylight. Cooling occurred on a few days and the demand was low. The reduction in demand in the modelled building (red line) was due to reduction in artificial light as daylight increased. The lighting in the library is controlled manually but is usually all on for the entire opening period. There is no daylight dimming, which explains the flat profile in the library figure 70b, black line. In the modelled building, the artificial lighting was reduced as the daylight increased (as was illustrated in figure 54).

7.3 Multiple building results

This section presents data from the multiple building model using the method described in section 6.4. Category 1 consisted of buildings of a single type: type 1, 1970, electric HVAC. These were expected to give the largest load shift during the winter. Category 2 relates to office buildings in Reading Borough constructed prior to the year 2000 and with gas / electric HVAC. Category 3 represents a subset of these within a 1 km diameter circle, all with gas / electric HVAC.

7.3.1 Category 1

This category simulated the load shift from a group of buildings all of the same type with the largest load shift during STOR season 5 (27th October to 2nd February 2015). This would be produced by a group of type 1, 1970's buildings with electric heating and cooling (case 7 in table 56, section 7.2.3). This simulation case had the largest load shift during the period covered by STOR seasons 2, 5 and 6 (28th April to 18th August 2014 and 27th October to 1st April 2015). The minimum size of service that can be provided under STOR is 3 MW (section 4.4.1). The winter is covered by STOR season 5 (27th October to 2nd February 2015) when the load reduction from a single type 1, 1970, electrically heated building was 16.55 kW (table 56). To obtain 3 MW reduction would require (3000 kW / 16.55 kW) = 181.3 buildings. The power difference (load shift) for a group of 182 of these buildings is illustrated in figure 71. The box plots show median and inter-quartile range (IQR) of the power difference for each timestep during a simulated DSM event. The variation within each season was due to the weather and variation in the parameter values. Each DSM event was from 17:00 to 18:00. The black broken line is the 95th percentile of power difference. The largest load shift occured during the period with the lowest outside temperatures (27th October to 2nd February 2015). This also gave a constant load reduction during the DSM period. The STOR season covering the warmest outside temperatures (28th April to 18th August 2014) gave a constant load reduction, due to cooling, though smaller than during the winter. The plots representing seasons 1, 3 and 4 (1st to 28th April and 18th August to 27th October) show the electrical load reducing for the first timestep before returning to (or exceeding) the baseline value. This relates to periods with more moderate outside temperatures and a lower demand for heating and cooling.

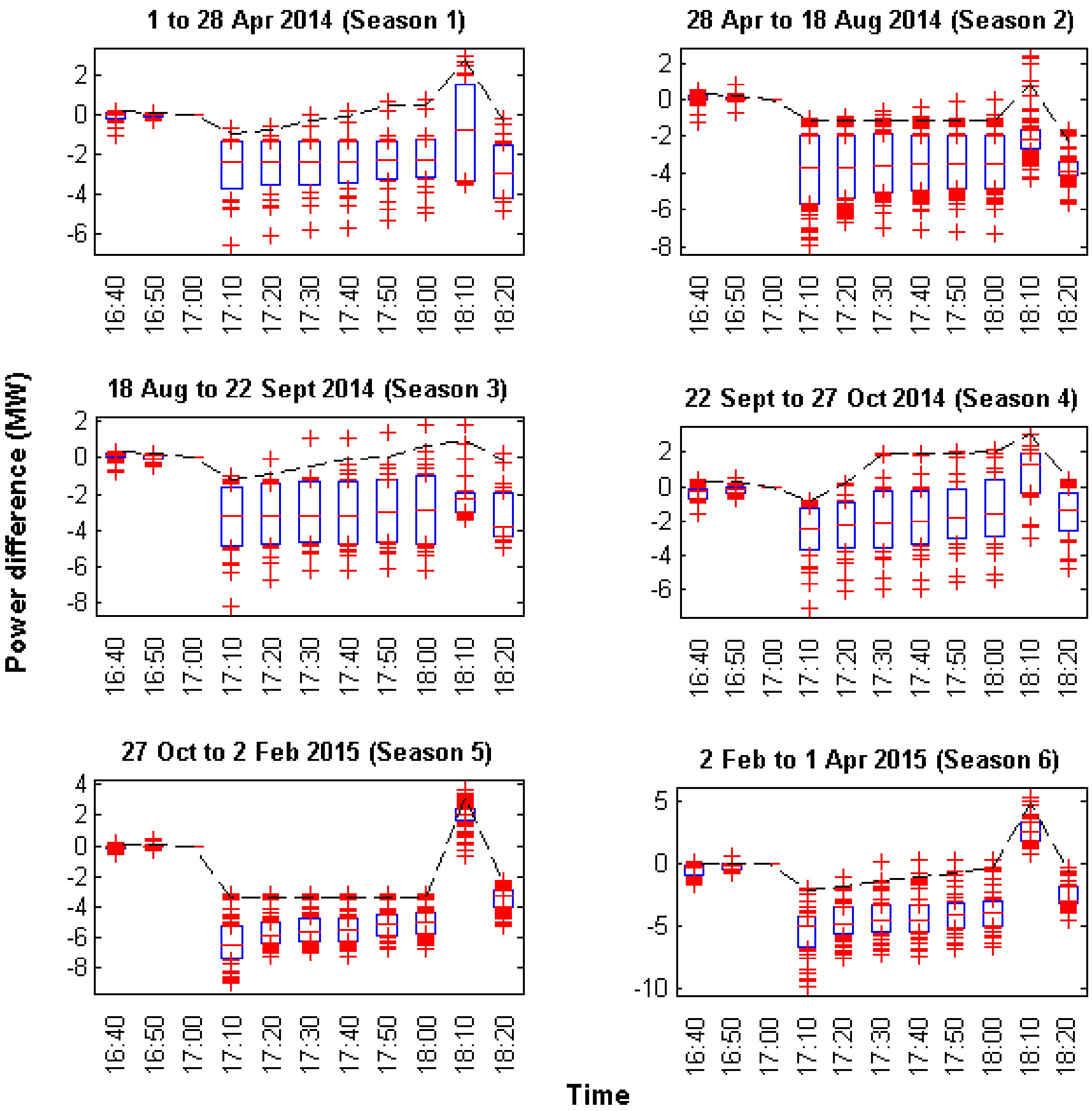


Figure 71 Load shift for 182 buildings, all type 1, 1970s build with electric HVAC. Each subplot represents the load shift during a STOR season.

7.3.1.1 NG STOR Results

This section evaluates the payments that National Grid would make if the buildings in category 1 collectively provided a STOR service. It is assumed that these 182 buildings supplied their service through an aggregator. The load reduction, illustrated in figure 71, was used to calculate the payments from National Grid for *availability* and *utilisation*. The 95th percentile of power difference (the black, broken line) was used as the threshold for load reduction since National Grid require service availability of at least 95% (section 4.4.1).

The '*delivered energy*' under STOR was calculated for each settlement period (SP) (half-hour) (as detailed in section 6.4.2.1). During the load shift period, the electrical power at each timestep was subtracted from the baseline power (the consumption at the start of the load shift period). In the calculations below related to STOR, when 'delivered energy' is positive the power consumption had reduced (it was less than the baseline) (table 57). A negative value in this table means that the 95th percentile of power increased above the baseline level during the settlement period. The 'delivered energy' in table 57, represents the load shift energy from a one-hour DSM event between 17:00 and 18:00 on any weekday during the specified season. The minimum load reduction that can be supplied under STOR is 3 MW (equivalent to 1.5 MWh for each settlement period) (section 4.4.1). This group of 182 simulated buildings only met this criterion during season 5.

If the companies providing this DSM service had tendered at least 20 minutes response time, the mean *utilisation* payment for 2014/2015 was £90 / MWh (section 4.4.1). The group of buildings would expect to receive £306.87 per event or a mean of £1.69 each. Supplying a STOR service 40 times a year (section 6.3.8) would earn each company an annual utilisation payment of £67.44. If these companies had tendered less than 20 minutes response time, the mean *utilisation* payment was £474.92. This is a mean of £104.38 per building per year.

Table 57 Load reduction and mean STOR Utilisation Payment for April 2014 to 2015.
Source: *National Grid (2014d)*

Season		Delivered Energy (MWh)		Utilisation Payment (£)	
		17:00 to 17:30	17:30 to 18:00	Response time > 20 mins	Response time < 20 mins
1	1st to 28th Apr 2014	0.342	-0.156	-	-
2	28th Apr to 18th Aug	0.553	0.544	-	-
3	18th Aug to 22nd Sept	0.452	-0.120	-	-
4	22nd Sept to 27th Oct	-0.208	-0.985	-	-
5	27th Oct to 2nd Feb 2015	1.715	1.694	£306.87	£474.92
6	2nd Feb to 1st Apr 2015	0.929	0.398	-	-

National Grid also make an *availability* payment (section 6.4.2.1). For providers who had tendered at least 20 minutes notice, the mean value for 2014/15 was £0.65 / MWh. This is multiplied by the number of settlement periods in each window where the service was offered and reduced by any penalty payments. It is assumed that no penalties had been imposed, that 3 MW of load reduction had been offered and that the STOR providers had offered service during window 2 in season 5. This window is from 16:00 to 21:00 and amounts to ten settlement periods (figure 11 in section 4.4.1). The mean availability payment for each tendered window would be (3 MW x £0.65 / MWh x 0.5 x 10 settlement periods =) £9.68. The '0.5' factor converts MWh to half-hour settlement periods. The mean *availability* payment for STOR providers with less than 20 minutes' response time was £26.99. For 40 'available' windows / year, the payment per building is £2.19/year or £5.93/year, with less than 20 minutes' notice.

7.3.2 Category 2

This category represents office buildings constructed up to year 2000 in Reading Borough. This consisted of 173 archetype buildings, all with gas heating (table 53 in section 6.4.1). Figure 72 illustrates the load-shift results for this 'population' for each STOR season. Each subplot shows the power difference during one STOR season. The broken black line is the 95th percentile of the load reduction. This was used to indicate the available load that could be provided to a STOR service.

The summer load shift appears small for a group of buildings with cooling. Subplot 2 (28th April to 18th August 2014) includes some hot days and some days when little or no cooling was required. This explains the large variation, shown by the height of the boxes for 17:10 to 18:00. If a high level of certainty is required, as with STOR, only a small reduction is possible. The load reduction across gas heated buildings was significant during July and August for those with 1990s fabric standards (figure 61). The older buildings, which made up 72% of this group (by floor area), had load reductions of less than 2 kW each.

The winter load shift was small but consistent. Subplot 5 (27th October to 2nd February 2015) represents a period for which there was little or no cooling. This load reduction resulted from HVAC pump and fan power being halved. Pumps were scheduled by heating; fans by occupancy which halved after 17:00 (section 6.3.4). There was no variation in the power consumption or the scheduling between sites of these end uses. This subplot indicates a consistent load reduction which would be ideal for STOR, if it were larger.

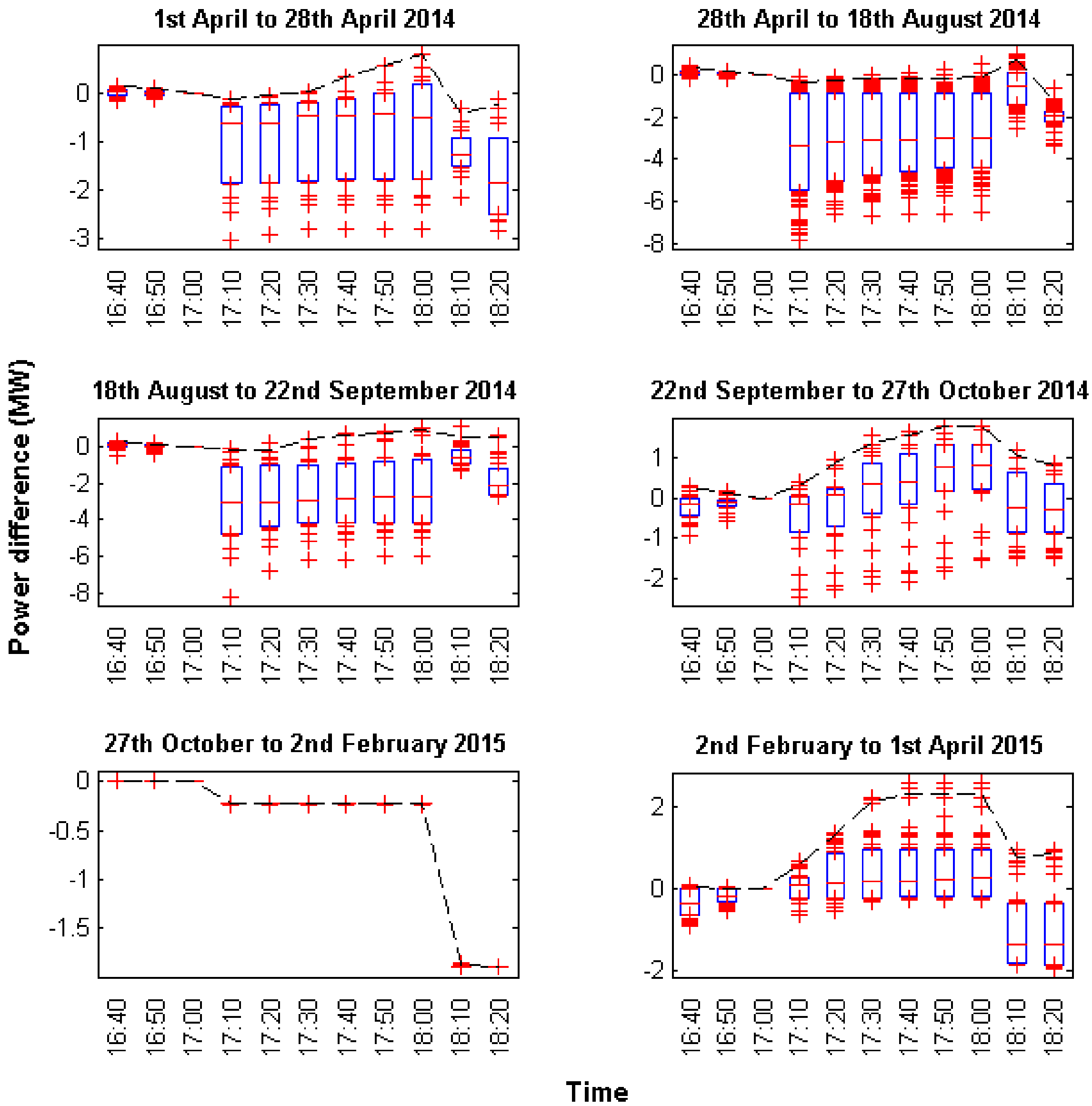


Figure 72 Load-shift for a group of office buildings in Reading constructed up to year 2000, represented by 173 archetype buildings with gas heating. The broken black line represents 95th percentile of power difference. Each subplot represents one STOR season.

7.3.2.1 NG STOR Results

The delivered energy for each settlement period (SP) was calculated, following the process in section 6.4.2.1. Figure 73 shows the median and IQR of the delivered energy for the settlement periods during the load shift period. The broken black line represents the minimum level for STOR (equivalent to 1.5 MWh/SP), which is taken as the '*expected* *energy'*. The 95th percentiles are shown by the black dotted line. The '*capped energy'* (the minimum of expected energy and delivered energy) is limited to 1.5 MWh per settlement period. These calculations have the effect of 'inverting' the power difference in figure 72. '*Delivered energy*' is the energy that National Grid would 'receive' from these buildings. A positive value of 'delivered energy' is equivalent to a load reduction.

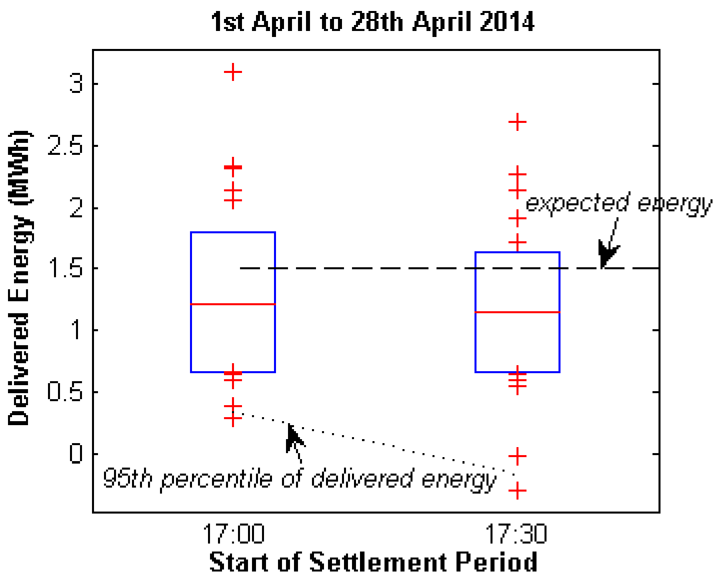


Figure 73 Example to illustrate '*delivered energy*' by a simulated DSM event and the minimum STOR requirement for '*expected energy*'. A positive value of '*delivered energy*' means a load reduction.

Figure 74 shows the median and IQR of these values calculated from the weekdays in each season. The broken black line represents the minimum level for STOR (equivalent to 1.5 MWh/SP), which is taken as the '*expected energy'*. The 95th percentiles are shown by the black dotted line. The '*capped energy'* (the minimum of expected energy and delivered energy) is limited to 1.5 MWh per settlement period.

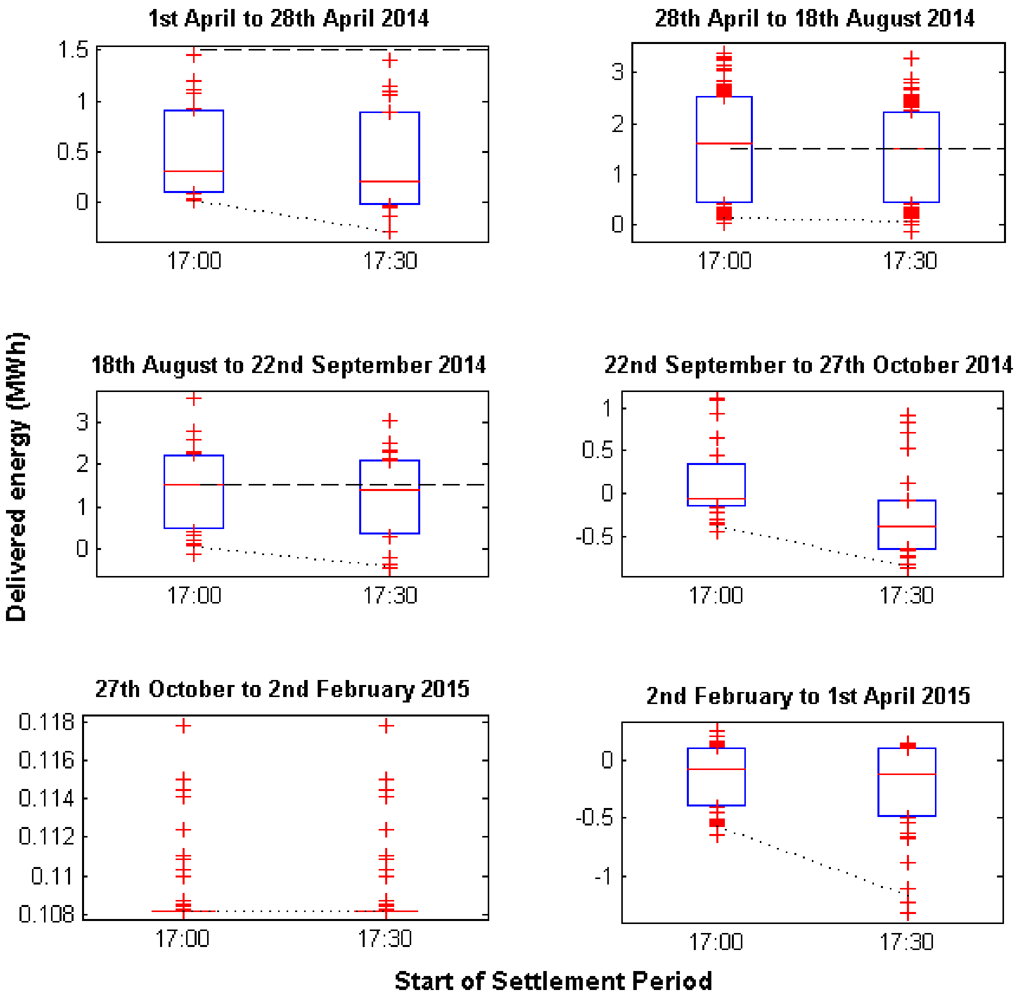


Figure 74 '*Delivered energy*' for National Grid's STOR service from load reductions in HVAC systems for a group of 173 office buildings in Reading. Each subplot represents a STOR season. A positive value of '*delivered energy*' means a load reduction.

The '*delivered energy'* for each settlement period is recorded in table 58. Positive values of 'delivered energy' indicate load reductions, which could contribute to a STOR service. A negative value represents a net increase in electricity consumption. In all seasons the 95th percentiles are less than the minimum for STOR, so no payment is made. Load reduction from heating and cooling from this group of gas heated buildings is insufficient to meet the minimum threshold for STOR.

Table 58 95th percentiles of '*delivered energy*' for National Grid's STOR service for model Category 2, representing office buildings in Reading with gas heating constructed up to 2001. Positive values indicate load reductions (energy that could be delivered under STOR).

Source: *National Grid (2014d)*

STOR Season		Delivered Energy (MWh) 17:00 to 17:30	17:30 to 18:00
1	1st to 28th Apr 2014	0.013	-0.295
2	28th Apr to 18th Aug	0.135	0.077
3	18th Aug to 22nd Sept	0.027	-0.398
4	22nd Sept to 27th Oct	-0.376	-0.839
5	27th Oct to 2nd Feb 2015	0.108	0.108
6	2nd Feb to 1st Apr 2015	-0.565	-1.165

7.3.2.2 DNO Results

The mean load shift during the DSM events was calculated. The 95th percentile of this energy was calculated using the method described for Project Falcon (section 6.4.2.2). Table 59 shows these data with the payment rate of £300 / MWh. This represents the payment due for a single DSM event of one hour each season.

Table 59 95th percentile of mean '*delivery*' for Project Falcon, for model Category 2, representing 173 office buildings in Reading with gas heating constructed up to year 2001. Positive values indicate load reductions. Source: *Swandells (2014)*

Season		Delivery (MWh) 17:00 to 18:00	Payment
1	1st to 28th Apr 2014	-0.282	-
2	28th Apr to 18th Aug	0.206	£61.78
3	18th Aug to 22nd Sept	-0.272	-
4	22nd Sept to 27th Oct	-1.078	-
5	27th Oct to 2nd Feb 2015	0.216	£64.90
6	2nd Feb to 1st Apr 2015	-1.771	-

The Project Falcon trial took place during the winter (1st November to end of February) (section 6.4.2.2). Up to 40 hours of DSM per business were assumed. Multiplying the above income for this period by 40 and dividing by the number of archetype buildings (173), gives a payment of £15 for the 27th October to 2nd February 2015.

7.3.2.3 Validity Tests

The total electricity consumption of the buildings in category 2, in the load shift scenario, was compared with profile data for small non-domestic electricity consumers. The electricity consumption from the model (in kWh) was aggregated into settlement periods. These data were compared with a profile of demand calculated using Elexon's regression coefficients for 'profile class 3' customers (small, non-domestic consumers) (section 6.3.9) and is shown in figure 75.

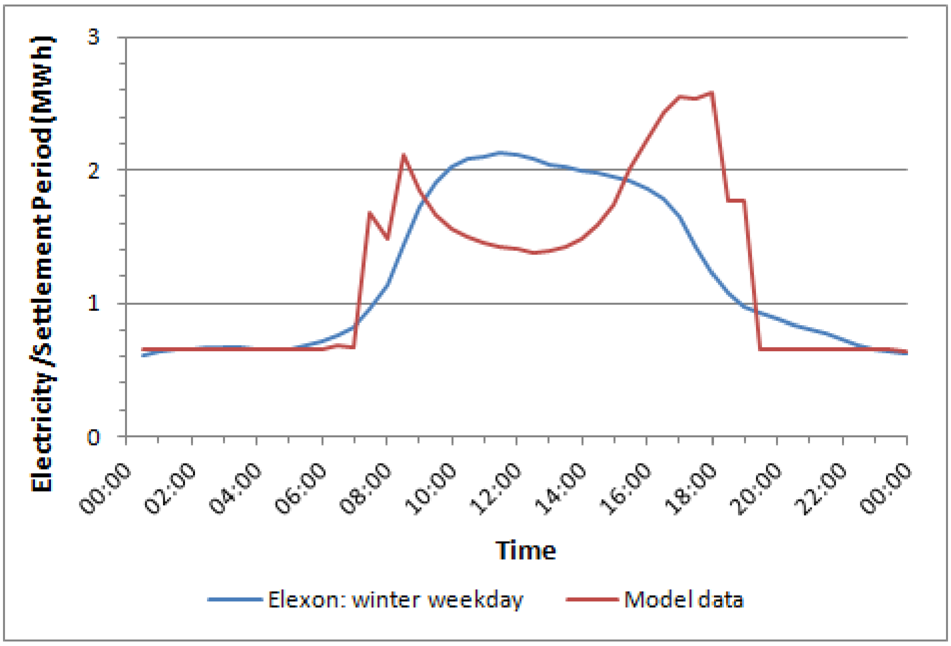


Figure 75 Modelled electricity consumption for office buildings in Reading constructed prior to 2001 (red line) and Elexon profile class 3 data (blue line). These data compare the mean consumption for weekdays from 26th October to 28th March 2015 (source: *Elexon*)

The daytime 'dip' in consumption in the model data was mainly due to a reduction in lighting demand in response to increased daylight. A small further reduction in building electricity for ventilation was due to the of 25% reduction in occupancy at lunchtime (section 6.3.4). The model assumed that electricity consumed for IT equipment was constant from 08:00 to 18:00, when a gradual decrease is more likely. Profile class 3 consumers are small non-domestic users and include any business activity, not just office work (section 4.2.1).

7.3.3 Category 3

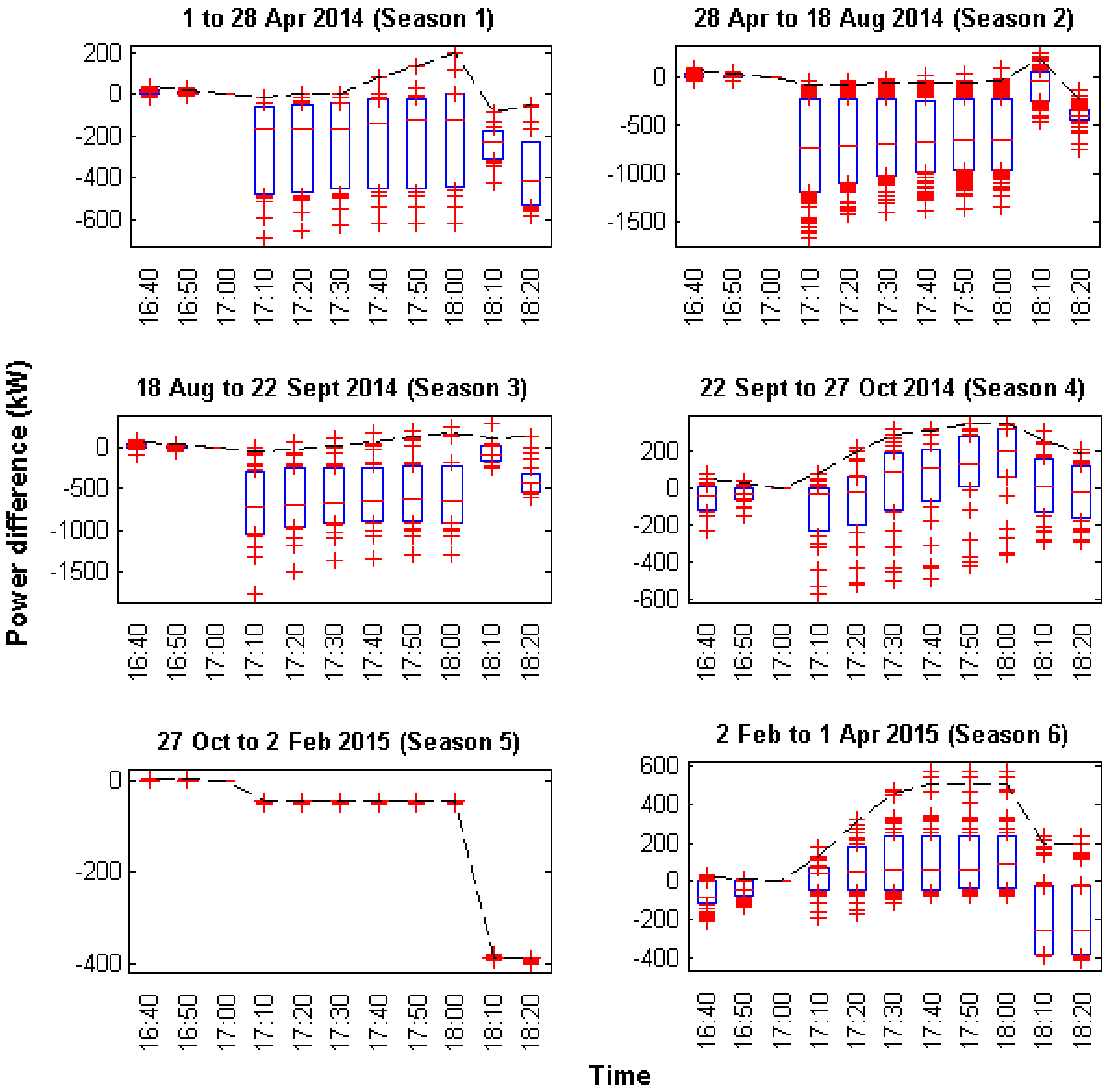


Figure 76 Load-shift for a group of office buildings in Reading constructed up to year 2000, represented by 38 archetype buildings with gas heating. The broken black line represents 95th percentile of power difference. Each subplot represents one STOR season.

Category 3 relates to office buildings present within a 1 km circle in Reading Borough and constructed up to year 2000 (section 6.4.1). Figure 76 illustrates the load-shift results for this ‘population’. The broken black line is the 95th percentile of the load reduction.

7.3.3.1 NG STOR Results

If the load reduction from all buildings in category 3 was aggregated it would fall short of the requirements for STOR. The minimum ‘*expected energy’* is 1.5 MWh per settlement period (SP) (3 MW). The 95th percentile values of power difference for each load shift period (from figure 76) were used to calculate the 'delivered energy'. This is the reduction in load compared with the baseline, immediately before the start of the load shift period. Delivered energy was calculated for each SP during the load shift period. Table 60 presents these data for by season. In each case, this is below the STOR threshold of 1.5 MWh/SP, so no payment would be paid.

Table 60 '*Delivered Energy*' under STOR for 38 archetype office buildings in model Category 3 (inside a 1 km circle in Reading). Positive values indicate load reductions (energy that could be delivered under STOR). Source: *National Grid (2014d)*

		***Delivered Energy* (MWh)**	
Season		17:00 to 17:30	17:30 to 18:00
1	1st to 28th Apr 2014	0.002	-0.068
2	28th Apr to 18th Aug	0.039	0.030
3	18th Aug to 22nd Sept	0.007	-0.062
4	22nd Sept to 27th Oct	-0.089	-0.167
5	27th Oct to 2nd Feb 2015	0.023	0.023
6	2nd Feb to 1st Apr 2015	-0.128	-0.252

7.3.3.2 DNO Results

The 95th percentile of the mean '*delivery*' during DSM events was calculated using the method described for Project Falcon (section 6.4.2.2). In order to understand seasonal variation and enable a comparison with STOR, these data were analysed by STOR season, table 61. Positive values of 'Delivery' refer to net load reduction in the 95th percentile values. The negative values for 'delivery' mean that the load increased overall. An example of this is shown in figure 76, season 1, where the 95th percentile of power difference falls slightly from 17:00 to 17:10, before increasing until 18:00.

Table 61 Mean energy delivered (95th percentile) for Project Falcon for model Category 3, representing 38 archetype office buildings in Reading with gas heating constructed up to year 2001. Positive values indicate load reductions. Source: *Swandells (2014)*

Season		Delivery (MWh)	Payment
1	1st to 28th Apr 2014	-0.066	-
2	28th Apr to 18th Aug	0.069	£20.74
3	18th Aug to 22nd Sept	-0.055	-
4	22nd Sept to 27th Oct	-0.247	-
5	27th Oct to 2nd Feb 2015	0.045	£13.55
6	2nd Feb to 1st Apr 2015	-0.377	-

The payments in table 61 were calculated at £300 / MWh (section 6.4.2.2). This represents the total payment for all buildings for a single one hour DSM event. WPD proposed that they would hold 40 hours of DSM events in their Falcon Trial during the winter (section 4.4.3). This scenario consisted of 38 buildings (section 6.4.1). The mean annual payment per building for 28th April to 18th August would be £21.83 and for 27th October to 2nd February: £14.26.

8. Discussion

8.1 Introduction

This thesis has modelled discretionary electrical load in offices and applied this to groups of buildings in order to match the requirements of System Operator or DNO stakeholders. The application of this to SMEs is of particular interest since many do not see enough value in energy management to implement changes. Chapter 2 noted that energy consumption from individual SMEs is often low, providing trivial incentive for reduction. DSM enabled by a smart grid may provide revenue opportunities as a result of switching flexible loads with respect to time. In order to examine the shiftable load, approaches to classifying non-domestic buildings were examined from the literature in chapter 3. These indicated that thermal loads in offices would be most suitable for DSM. Any attempt to quantify thermal electrical loads, requires that flexible end uses are identifiable separately and in a time series. Aggregating these loads and matching them to the requirements of a DNO or the System Operator was discussed in chapter 4. Chapter 5 categorised existing modelling approaches and proposed a building physics model with reduced parameters and a statistical overlay. This method was developed in chapter 6, with results from simulating energy in office buildings presented in chapter 7.

This chapter discusses the simulations for single buildings (section 8.2.1) and for groups (section 8.2.2). The implications for the model design and classification approach are discussed in section 8.4. Analysis of the revenue implications for building occupiers and for local authorities is discussed in section 8.5. Limitations of this research and suggestions for further work are given in section 8.6. Conclusions are outlined in the following chapter.

8.2 DSM and Thermal Loads in Office Buildings

This section analyses the simulation results and compares them with the literature. The emphasis is on the '*relative accuracy*' of model outputs rather than the absolute values (Yao & Steemers 2013). The complexity of occupant, HVAC system, building and environmental interactions mean that many factors are outside the scope of the model. However absolute values of model parameters are important in deciding the applicability of the model. For example internal building temperatures are essential in evaluating occupant comfort and costs are needed to determine a business case for DSM.

8.2.1 Single Buildings

The energy consumption of the model cases was consistent with the benchmarks in TM46 (Field et al. 2008). The recent analysis of DECs (Hong & Steadman 2013) shows these benchmarks to be reasonable. The gas heated 1980s cases in BaU scenario had similar energy consumption to these benchmarks (section 6.3.7.2). Energy consumption in the 1970s and 1990s cases was correspondingly higher or lower by 30 to 38% due to the building fabric. The electric heated cases had higher heating and cooling CoPs for all age bands. This resulted in annual energy consumption in the BaU scenario that was between 33% less and 8% more than the benchmark.

Building temperatures in office areas were maintained within the defined comfort band in the BaU scenario and with small deviations in the load shift scenario. The heating and cooling for the same period is illustrated in figure 29. As expected, the summer thermal load is dominated by cooling which is driven by the outside temperature. and figure 33 in section 6.3.7.3 show the close relationship between temperatures in individual zones and the building mean. The mean temperature is affected by the non-working 'common areas' which have less strict temperature control, so may be warmer or cooler than office areas. In the load shift scenario, for a small number of hours each year, the temperature was outside the 21°C to 24°C band. In all cases, the temperature was above 18°C and below 27°C for all occupied hours (section 7.2.2). In the NTVV trial, the temperature setpoints were changed by ±2 °C (Stannard & Hewitt 2014). SSEPD acknowledge that further investigation is required to understand the relationship between the action of turning down HVAC equipment, occupant comfort and the reduction in load.

Newer building had more shiftable load during the summer and less during the winter. For the buildings heated by gas, the shiftable load consisted of cooling and HVAC pumps. During July and August, the 1990s buildings had a load reduction of 10 to 12 kW (figure 61 in section 7.2.3). For the 1970s and 1980s buildings the load reduction during July was 1 to 2 kW and zero during August. For the electrically heated buildings, the shiftable loads consisted of heating, cooling and HVAC pumps. During January and December, load reductions of 10 kW to 22 kW were recorded from the 1970s and 1980s cases (figure 62 in section 7.2.3). However this was lower with the 1990s buildings (8 kW to 12 kW). This suggests that if older buildings are retro-fitted with insulation to Part L 1995 (DEWO 1995), there is a greater risk of over-heating in the summer. If cooling is installed, then there will be significantly more demand for cooling than with the current minimal insulation. This also points to more flexible load on hot days. Improving the insulation to the same standard would reduce the heating demand and the load available for time shifting on cooler days. The energy source used for heating is more significant in determining the load shift in office buildings than the age band or built form type.

During March, April, September and October, there was a net increase in building electrical load during the load shift period. In order to maintain acceptable temperatures, heating or cooling sometimes came on during the load shift period and negated any reduction, as with figure 56 in section 7.2.1. A smaller demand for heating and cooling meant that less load reduction was possible.

During January, November and December, there was little load shift with gas heated buildings, since there was little cooling and the only flexible load in this model was HVAC pumps (figure 61 in section 7.2.3). The open plan types (1 and 3) had marginally larger reductions than the cellular types (2 and 4), because the model assumed that the air within any room was all at the same temperature.

The requirement for DSM during the summer is likely to become more important, especially for DNOs due to localised peaks in demand. In some parts of the electricity network, such as London, the highest demand is already during the summer due to cooling loads (Frontier Economics 2015). If climate change leads to more hot days, the mean cooling load is likely to increase. The 'rating' of cables and transformers (the maximum permitted power) depends partly on the external temperature since this affects the rate of heat removal (Evans & Bessant 2014). For similar load profiles, this rating limit is more likely to be reached during the summer than the winter. These effects are likely to be concentrated in commercial areas with a high concentration of cooling systems.

The load reductions observed in the model are similar to those recorded in a recent trial but there is insufficient data to make direct comparisons. During the NTVV trial, air-conditioning loads were turned down automatically (section 3.5.3.3). For the load shift events of one-hour duration, the reduction was 0 kW to 51 kW. Details of the participating organisations, such as the number of staff or their operating hours are not stated. This compares with modelled load reductions of 15 to 20 kW in 1970s buildings with electric heating during January and December and around 10 kW in 1990s buildings. The model data consists of 95^{th} percentiles. SSEPD noted that for some participants there were large variations in demand reduction (section 3.5.3.3).

Future scenarios are more likely to be amenable to DSM if more buildings have cooling or electric heating. More electric heating is predicted by 2035 (section 4.3). Storage heaters show that a substantial amount of heating load can be shifted in time. Other studies have indicated that savings from DSM are sensitive to many factors. For example, Braun (2003) states that DSM savings for cooling are affected by electricity company prices, occupancy schedule, building construction, HVAC equipment, climate and control strategy.

8.2.2 Groups of Buildings

A large group of office buildings could offer a DSM service to the System Operator but achieving this by reducing demand from HVAC systems alone is unlikely. In multiple buildings category 1, a group of 182 buildings would have a total load reduction of 3 MW during STOR season 5, 27^{th} October to 2^{nd} February 2015 (figure 71 in section 7.3.1). This represented a group of lightly insulated (1970s fabric) buildings with electric heating (figure 62). During other STOR seasons, this minimum level was unlikely to be met.

Additional demand reduction or generation would be needed to meet the requirements for STOR. A large proportion of STOR is currently provided by on-site generation (section 4.4.1)

The payment for STOR was low (section 4.4.1). With Category 2, (section 7.3.2) there was insufficient demand reduction from simulated office buildings to supply the minimum STOR service (3 MW). Category 2 represented all office buildings constructed before 2001 in Reading with gas heating and electric cooling. This was wider than a single sub-station but within a single DNO area. With categories 2 and 3 the HVAC was gas heating and electric cooling.

Analysing the load shift by STOR season (table 56 in section 7.2.3) gave a smaller load reduction than the month by month analysis (figure 61 and figure 62). Apart from season 1 (1^{st} to 28^{th} April 2015), each season is longer than a month (table 62). If the DSM service is STOR, then analysis by STOR season is reasonable, especially if the STOR contract is '*committed*' (section 4.4.1). In this case, the company providing the DSM has to be able to provide a service during all STOR windows. With '*flexible*' STOR contracts, a service provider can select the windows they wish to offer service to. Here analysis by month alongside analysis by season could help a providing company to choose the right contract. DNOs are not yet offering commercial DSM services. Their requirements for load reduction are driven by peak demand at sub-stations or faults with equipment, not by the timing of STOR seasons (section 4.3.1).

Table 62 STOR Seasons for 2014 / 15

Season	Dates
1	1^{st} to 28^{th} April 2014
2	28^{th} April to 18^{th} Aug 2014
3	18^{th} Aug to 22^{nd} Sept 2014
4	22^{nd} Sept to 27^{th} Oct 2014
5	27^{th} Oct to 2^{nd} Feb 2015
6	2^{nd} Feb to 1^{st} April 2015

Source: *National Grid (2014d)*

In both sets of analysis by (month and by STOR season), 95^{th} percentiles were used to indicate the available load shift. This was due to the high availability requirements of both System Operator and DNO (section 4.4.1 and 4.4.3). An *aggregator* would manage the risk of ‘under provision’ by grouping load reduction in excess of that required by their NG contract. The characteristics of the reduction would depend on exactly what types of loads were being aggregated and the operating conditions within each providing company.

DNOs do not yet have definite requirements for DSM. DNOs are evaluating where DSM would be appropriate, informed by recent customer trials (section 4.4.3). The emphasis has been on exploring what load reduction could be achieved, rather than on achieving a target. SSEPD state the size of demand reduction at individual sites but do not comment on how this relates to their needs (Stannard & Hewitt 2014). 20 kW reduction was a typical demand reduction for one hour achieved during a trial, with no financial incentive. WPD suggest 1 MW reduction might be required at an 11 kV sub-station but this will depend on the load on an individual transformer (section 4.4.3). These factors make it impossible to state how much of a DNO’s requirement for DSM could be met by load reduction from a group of office buildings.

Tariffs for the electricity consumed by SMEs are expected to reflect the wholesale price as new meters are installed and new contacts are agreed (section 4.2.1). SMEs with smart (or advanced) meters will pay higher unit rates during DNO ‘red’ bands. In Reading, this applies from 16:30 to 19:00 on weekdays, including bank holidays throughout the year. An opportunity exists for SMEs to save money if they can reduce demand during these periods. According to Western Power Distribution (WPD), a large electricity consumer could save more money from avoided network charges than it would receive in compensation from WPD for its load reduction (section 4.4.3). This introduces the concept of demand management to SMEs without the requirement to negotiate a DSM contract with minimum thresholds and penalties.

A group of buildings may be able to offer a DSM service for less than one hour. A load reduction of 10 or 20 minutes may be possible during spring and autumn (1st April to 28th and 18th August to 22nd September) (section 7.2.4.1). It was suggested in section 3.4.3 that cooling could be reduced for 30 minutes and heating for 15 minutes. The modelled load shift of one hour was based on the duration of DSM events in National Grid’s STOR service (section 4.4.1) and in DNO trials (section 4.4.3). Since there is not yet a commercial DSM service from any DNO, the duration of the load reduction they would require is unknown. The shortest DSM events in the NTVV trial were for 30 minutes (and the longest for 2 hours) (Stannard & Hewitt 2014). Some organisations provide DSM for a few minutes at a time, such as University of East Anglia (section 3.5.3). National Grid’s ‘Firm Frequency Response’ (FFR) service, which may be provided through an aggregator, typically requires load reductions for 5 minutes or less (Open Energi 2015b).

Reading has a large number of companies operating in the IT and communications sector; some of which have significant ‘back office’ IT systems (section 1.3). These systems constitute larger IT and cooling loads than in the offices represented in the model. Power is also consumed by cooling systems all year and back-up is often provided by generators or batteries. Brown et al. (2008) point to the substantial and increasing power demand of data centres. Data centre IT equipment can consume ‘*from about 10 to almost 100 Watts per square foot*’ (108 W/m^2 to 1080 W/m^2) (Greenberg et al. 2006). Typically the cooling load doubles this. In comparison, the IT electricity demand used in this research was (10 W/m^2) (section 6.3.4). Data centre IT equipment is usually in use 24 hours a day but the associated cooling load may be flexible for at least half an hour. Back-up power is often installed and this may support DSM without affecting the operation of the business (Grünewald & Torriti 2013).

DSM from load reduction in offices is currently small but is potentially an important part of the total contribution, when other business activities and generation are added. KiWi Power, an electricity demand aggregator, is developing an innovative building management system which will help SMEs to participate in DSM (KiWi Power n.d.). This lower cost system will enable SMEs '*to control and automate energy production and consumption while participating in a localised energy market'*. Some companies will have flexible process loads such as, steam generation, hot water production or motors for industrial plant.

8.3 Strengths and Weaknesses of this Modelling Approach

8.3.1 Using a reduced parameter building physics model with statistical overlay

The term '*reduced parameter*' refers to the use of a model with four built form types to represent 67% of the non-domestic building stock (section 6.3) and a simplified approach to HVAC which calculated ideal building loads and applied constant CoP values (section 6.3.6). The strength of this approach was the reduced requirement for spatial and geometric data. Four built form types were used to represent basic geometric forms and space use (open plan or cellular), based on previous research (section 5.2.1.1). The simplified representation of HVAC systems calculated the heating and cooling loads without requiring details of the system components.

The simplified HVAC system generated unrealistic transient demand but the effect on the steady-state DSM was negligible. The HVAC system was represented in an idealised manner (section 6.3.6) which '*assumed that the ideal system can always meet the zone load'* (EnergyPlus 2012b, p.391). This resulted in higher transient heating and cooling demand than would be expected in real buildings (for example figure 50 in section 7.2.1). The effect of this was to create spikes in demand after 'turn on' or return to 'normal' following a DSM event. However the effect on the steady state DSM load was small.

The heating and cooling CoP values for the ASHP systems were fixed regardless of building age or time of year. These are indicative values and would be expected to vary as the outdoor temperature varies.

The built form types were assumed to be representative of buildings in a large population. If a small enough area is chosen, the distribution will not be valid. The built form types were based on surveys carried out in the 1990s and were assumed to still exist in these proportions. Reasonable values for occupancy schedules, fabric design and HVAC design were chosen based on the literature (sections 6.3.2 to 0) but not proven to represent the office building stock of Reading. The burden of data input in the simplified model was still considerable. These may not be consistent or applicable together.

The effect of human behaviour was not adequately represented through the use of parameters (section 6.3.5). This is an inherent weakness of a building physics model: '*occupant behaviour must be estimated which is difficult as behaviour has been shown to vary widely and in unpredictable ways*' (Swan & Ugursal 2009). Section 5.2.3 indicated that occupant behaviour may affect annual energy consumption by a factor of at least two.

8.3.2 Implementation of the Model with Publicly Available Software

The term '*publicly available software*' refers to the simulation engine EnergyPlus which was used with DesignBuilder and jEPlus (section 6.3.6). DesignBuilder provided a graphical interface for initial development and jEPlus managed the parametric simulations with EnergyPlus. An alternative approach which the researcher considered was to represent a building using a resistive - capacitive (R-C) circuit model. This section considers the strengths and weaknesses of using 'off the shelf' tools rather than developing a bespoke tool.

The choice of a publicly available software tool, took advantage of extensive development and testing. The US Government supported the development of two building simulation programs, DOE-2 and BLAST, which were first published in late 1960's and early 1970's (Crawley et al. 2001). EnergyPlus combined features from these programs and was released in 2001. EnergyPlus has undergone comparative testing, including a trial with 19 other simulation programs (Crawley et al. 2005). Validation of EnergyPlus has compared the output with international standards (US Department of Energy 2014). EnergyPlus has been used in an extensive range of peer reviewed research (US Department of Energy 2011). DesignBuilder is a mature tool which has been tested against international standards (DesignBuilder n.d.). jEPlus was first released in 2009 and has been used in peer reviewed research (Zhang & Korolija 2014).

The implementation of the model using ‘off the shelf’ software produced a ‘portable’ tool. EnergyPlus, DesignBuilder and jEPlus can be operated on a variety of hardware and software platforms and these requirements are documented. This software is supported by detailed documentation and online forums (section 6.3.6). This makes it easier for other researchers to replicate the model described in this thesis and perform similar simulations. This accessibility supports the Open Access Requirements of the Engineering and Physical Sciences Research Council (EPSRC) (EPSRC 2014).

DesignBuilder enabled the rapid development of building models. The graphical interface made the process of creating and visualising buildings straightforward. A large set of default parameters established details of the building fabric, occupancy schedules and HVAC system. The building layout, including separation into zones was visible and readily verifiable. The comprehensive library of materials and building services with validated properties in DesignBuilder simplified the task of identifying input data for the model. DesignBuilder post processed the EnergyPlus simulation output making it more accessible than the raw data. DesignBuilder pre-selected data from the simulation and calculated higher level outputs (such as mean building temperature), presenting these in an accessible tabular or graphical format. jEPlus enabled faster execution of many simulations with different parameter values than would have been possible with DesignBuilder.

DesignBuilder automatically attributes many factors relating to the fabric, schedules and HVAC to the building under development which may introduce inappropriate values. Although DesignBuilder simplifies the data entry compared with working directly with EnergyPlus, it is still complex and time-consuming to identify a factor that needs to be changed or how to change it.

In order to run parametric simulations using jEPlus, the input data file (IDF) describing the building had to be edited (section 6.3.6). The IDF is a text file which took some effort to understand. Entering the search strings for the parameters was time-consuming due to the number of zones and floors chosen. The risk of entering data incorrectly was high compared with DesignBuilder, since no error check is made until run-time. This resulted in some simulations failing or generating meaningless data.

The intention with using a commercial modelling tool was to minimise the detail inherent in a building. In the process of developing this model, it was necessary to understand a number of features of EnergyPlus, which drew the researcher into this complexity, such as how the HVAC system was sized.

A large number of data outputs are available with EnergyPlus. It was not straightforward to identify the appropriate ones since most did not relate directly to the outputs generated by DesignBuilder. In general EnergyPlus outputs were at a lower level than those from Designbuilder (for example, heating energy in a single zone for a timestep) and it was necessary to evaluate how to convert these into recognisable data (table 41).

8.4 Model Design and Classification of Buildings

How does the analysis inform the model design?

Although the model was simplified there was still a need for energy consumption data to verify the model output. A greater number of simulated building cases should be validated with measured building data so that the model can be adjusted.

How should this inform the development of a future model?

In developing a similar model to assess DSM opportunities, it is suggested that initially the simplest possible representation of an office building is used. This should consist of one geometric type: a square building which has equal solar gain and wind exposure on all sides. This should have one floor, divided into one zone for office work. Complexity in the form of additional floors and zones can be added and the effect of these changes on the shiftable load understood. This simpler model would make the EnergyPlus input file shorter and easier to edit for parametric simulations. There would be fewer outputs (as fewer zones) which would simplify the process of checking the model output.

8.5 SMEs and Local Authorities

8.5.1 Implications for SMEs

Offices with large cooling loads are best placed to contribute to DSM. Cooling for general office space can provide flexible load but this is only significant in 1990s buildings (figure 61 in section 7.2.3). Buildings with additional cooling for IT systems or back-up power have greater DSM potential. Electric heating offers more flexible load during the winter. A group of organisations on a business park, including SMEs, could shift loads away from peak periods to reduce the load at the sub-station. To what extent this would support the

DNO's need for DSM is unclear because DNOs are at an early stage in developing their requirements.

The incentives for SMEs to shift heating and cooling loads are currently small. The income from load shifting of space heating and cooling is small with the present building stock. Taking the example of office buildings in Reading (category 2) supplying a service to a DNO (section 7.3.2.2), the DNO payment was £15 per building for the winter trial period, assuming 40 hours of DSM (section 7.3.2.2). The mean annual electricity consumption for the gas heated cases in the BaU scenario, was 101 to 118 MWh / building (section 6.3.7.2). The cost of this electricity for each building is in the range: £11.5k to £13.3k / year using DECC's price of 11.36 p/kWh for '*small*' consumers in Q3.2014 excluding the Climate Change Levy (DECC 2014d). '*Small*' consumption is classed as: 20 to 499 MWh/year.

There is a need to make DSM contracts straightforward and low risk in order to attract SMEs. Section 4.4.1 noted the complexity of the contract for STOR with penalty payments for failing to deliver at least 95% of the energy agreed. Since STOR contracts are agreed as part of a bid process, there is no guarantee of regular income (section 4.4.1). A DNO managing a DSM trial noted that a potential participant that was an SME lacked the legal resources to review its contract (Stannard & Hewitt 2014). SMEs that are tenants in multi-occupied buildings are unlikely to be responsible for controlling the heating and cooling to the building.

Recent UK DSM experience highlights that little DSM is from load shifting, especially with SMEs (section 4.4.1). This is consistent with the low level of DSM from the model. Section 4.4.1 described NG's STOR service and highlighted the small proportion of it supplied by load reduction. Section 4.4.3 detailed the problems experienced by a DNO wanting to engage SMEs in DSM.

The flexible load from HVAC in offices is likely to increase but the magnitude of this is uncertain. The literature examined in section 3.5.3.1 indicated that the proportion of office buildings with cooling has increased from 20% to around 60% in approximately 12 years. This may continue to rise but the level will saturate as HVAC will not be installed in every office building. Variable speed controls are more likely to be installed in new or refurbished HVAC systems due to the availability of Enhanced Capital Allowances (Carbon Trust 2014). The number of heat pumps installed in offices could become significant by 2035 if the capital costs are reduced and financial incentives continue (National Grid 2015a). This highlights the need to survey property to determine the quantity and distribution of HVAC systems and the potential for flexible load.

Smart grids may raise awareness of electricity consumption which could help to focus resources. SMEs are often small energy consumers with little financial incentive to save energy. The potential to save or make money may encourage some SMEs to save energy.

8.5.2 Opportunities for Local Authorities

A DNO's requirements for peak demand reduction are specific to each location. This points to business parks offering DSM, rather than solely SMEs. This suggests that a local authority may have a role in informing businesses about smart grids and the broader problems for DNOs of managing peak demands. Local authorities can facilitate communication between the DNO and local businesses. Local authorities have an important role in promoting carbon reduction and DSM supports this agenda (section 1.3). Local authorities such as Reading Borough Council have recognised the need to engage local businesses about smart networks and DSM.

A local authority can support a DNO's analysis of network constraints. The DNO will investigate where there is a lack of capacity on its network and whether DSM will mitigate this (Ward et al. 2012, p.32). Information on demand growth that the local authority can provide would support this. If a business case can be made for DSM by deferring investment, the DNO will identify the affected sub-stations and cables (Stannard 2013). The DNO will identify the buildings connected to this plant in order to contact the occupiers. As the DNO, they are unlikely to have contact details for many of these. In the NTVV Project, SEPD collaborated with the local authority, the chamber of commerce and facilities management groups in this regard. SEPD recognised the co-operation with Bracknell Forest Council as '*hugely beneficial'* (Stannard 2013). The Council provided contact details for 12% of the companies that took part in the NTVV trial and added some of its own buildings.

A local authority can inform developers and landlords of opportunities to make or save money with DSM facilitated by a smart network. A local authority can facilitate communication between developers and the DNO on planned development and network constraints (Evans & Bessant 2014, p.36). The developers can inform the DNO of the timescales, location and types of energy consuming and generating equipment planned. This can help the DNO to model network growth and plan future investment in network infrastructure. A building developer may be able to minimise network connection costs if they know the geographic locations of constraint areas on the DNO network before applying for connections.

A local authority could use network constraint information from a DNO to help manage the expectations of local residents and businesses (Evans & Bessant 2014). This includes peak time effects from consumer demand and weather related constraints from dense concentrations of small scale renewable energy systems. Information on network constraints could be used by a local authority to reduce the frustration of businesses and residents affected by power outages. The local authority could use this information to inform and educate businesses in those areas about DSM and carbon reduction.

When no immediate building refurbishment is planned, the local authority can inform landlords and agents of the benefits of smart grids and DSM. The local authority can inform these organisations on what a smart grid is and the approximate timescales (RCCP 2013a). The local authority can educate building managers of the requirements for building controls and network communications equipment to enable them to connect flexible loads to a smart network.

8.6 Limitations and Further Work

This study of DSM opportunities with SMEs in office buildings could be extended to other business activities but additional building types need to be considered. The four built form types were chosen because they relate to UK office buildings. For other business categories the relevance of these types to the building stock should be evaluated. For example, if retail buildings were considered, ‘sheds’ should be added to represent large, open plan low rise buildings.

The modelling of DSM in office buildings could be expanded. The effect of pre-heating the building prior to a DSM period in winter (and pre-cooling in summer) should be considered as was evaluated by Braun (2003), for example. This thesis considered DSM periods of one hour (from 17:00 to 18:00 only). DSM for 2 hours or more should be modelled, in line with the requirements of STOR. DSM should be modelled at other times of day, such as the morning peak in order to test the potential to supply service during other STOR windows (section 4.4.1).

A limitation of this model is that occupant comfort is only represented by a single parameter. The mean temperature only gives an indication of thermal comfort and says nothing about localised over-heating due, for example, to solar gain. This could be tested for a single building model with a sensitivity test that separates the building into one zone for each compass direction plus a central zone. The temperature in each zone can be compared with the mean to indicate the risk of the occupants being too hot or too cold. This would indicate more acceptable mean temperature thresholds for comfort.

The variation of human behaviour should be accounted for more thoroughly. The building occupancy schedules could be varied to account for differences in work patterns. Wider parameter variation, especially of infiltration and ventilation should represent actual buildings.

The analysis of HVAC systems should be expanded in scenarios for 2020 and 2030. These would include a higher proportion of buildings with gas heat / electric cool and heat pumps as suggested in National Grid (2015a). A wider range of combinations of primary and secondary HVAC systems could be included.

The data on the office building stock in Reading needs updating in order to present a clearer picture of the DSM potential from HVAC. A GIS model of building footprint, combined with LiDAR data on building heights is suggested to determine floor area and built form type. Local knowledge and sample external surveys would be needed to verify age bands, uses of buildings and separation of individual buildings with multiple uses.

The effect of neighbouring buildings on discretionary load could be evaluated. Measured data on building heights, over-shading and glazing would be required for specific locations under investigation. This would enable the model output to indicate the DSM potential in business parks.

The geographical scope of the model was limited to Reading in order to demonstrate the feasibility of this modelling approach and deliver recommendations to RBC. This model should be evaluated in areas of the UK, some distance from Reading, using the weather files for those locations and data on the local building stock. This will give a broader view of the application of DSM across the UK.

The carbon impact of load shifting was discussed only briefly in section 3.4.3. This could be expanded by analysing the change in carbon emissions from load shifting.

This study considers DSM solely in terms of discretionary loads being shifted in time in response to a ‘trigger’ from the DNO or System Operator. Other DSM opportunities are suggested in Chapter 4 such as time of use tariffs. These are currently being studied by DNOs, such as, Northern Powergrid, and should be evaluated for potential load shift (Sidebotham 2015).

9. Conclusion

9.1 Introduction

The aim of this thesis is:

To develop a method to quantify demand side management opportunities from SMEs in Reading Borough

This aim has been met through five supporting objectives which are reproduced in sections 9.2 to 9.6 below. Existing research on SME carbon reduction has been analysed in the context of smart grid development (section 9.2). This highlighted the heterogeneity of SMEs and non-domestic buildings and that energy is often a low or unknown cost. In order to break this problem down, previous research on classifying buildings and business activities was analysed (section 9.3). This was combined with published data on energy consumption which indicated that heating and cooling loads in office buildings contained the largest portion of flexible load. In order to investigate this, a dynamic model was developed to represent groups of buildings and simulate the effect of reducing the space conditioning loads for one hour (section 9.4). 24 building cases were developed to represent the majority of the stock and used to simulate groups of buildings (section 9.5). Recommendations were developed for RBC with application for SMEs and landlords (section 9.6). The implications for other business types and future years were considered.

9.2 SMEs, Energy and Smart Grids

Objective 1:

- *To find out what is already known about SME business activity, energy consumption and carbon reduction approaches in order to identify DSM opportunities with smart grids*

The vast majority of companies in the UK are SMEs (section 1.2). SMEs and the buildings they occupy are diverse. SMEs are often small energy consumers but their overall consumption is significant. Existing policies on energy, such as CRC and EU-ETS, affect only large companies or large consumers. Individual SMEs often stand to receive a trivial reward from energy saving.

SMEs often rent premises on short leases. Landlords could invest in energy saving but the current lease arrangements do not provide a means to recover this investment from tenants. Collective engagement of groups of SMEs with their landlords is needed in order to make a significant reduction in energy.

Reasons SMEs have not invested in energy efficiency measures amount to lack of resources, lack of information on energy and incentives split between landlords and tenants (section 2.5). Smart grids may help SMEs and landlords to overcome barriers to energy reduction as indicated in table 63. Energy is often a hidden cost for building tenants, included in the service charge or in estimated bills. A smart network provides data on real-time electricity consumption (item 2). Interpretation of data into information may need external advice which a local authority could contribute to (section 9.6). A company may divert money and time into energy saving if incentives from time-related tariffs are sufficiently strong (item 1). Smart grids provide landlords and tenants with data on energy consumption (item 3). If a suitable framework for co-operation is found, this could facilitate DSM.

Table 63 Opportunities with SMEs for DSM

	SME reasons for not energy saving	DSM from smart grids
1	Lack of sufficient financial incentive Lack of time	Opportunity for new tariffs to make or save money from load shifting consumption
2	Lack of information on energy consumption	Smart grid supplies near real time data on energy consumption
3	Landlord – tenant split incentives	Provides an opportunity to make or save money if a framework for co-operation can be agreed

9.3 Classification of Buildings to Identify DSM Opportunities

Objective 2:

- *To classify buildings and businesses in order to highlight demand side management (DSM) opportunities with smart grids*

Non-domestic buildings are heterogeneous and the factors affecting DSM are inter-related. Built form, building fabric standard, business activity and HVAC type affect the shiftable load and the relationships between them are poorly defined. This is complicated by the presence of multiple businesses in a single building, which is especially likely with small organisations.

The review of the literature on non-domestic building classification identified typologies which were used in this research. Four built form types and one business activity (office) from the NDBS Project were adopted. These take account of plan depth (narrow or deep) and how space is used (open plan or cellular) in all office buildings. Two HVAC types were used: (a) gas boiler and electric chiller and (b) ASHP. The secondary systems in both cases were DOAS with variable flow fan. The age band of construction was taken as a proxy for the building fabric standard. However the age band breakdown at a national level has not been updated for over 10 years and the extent of refurbishment is unknown.

The lack of recent data is a significant problem, especially relating to the end uses of energy. Analysis from the literature indicated that around 54% of UK office buildings currently have gas heating, cooling and mechanical ventilation (section 3.5.3.1). The extent of cooling has increased since 1990's, especially in larger properties. This group is of most interest for DSM. There is considerable uncertainty around the proportion of cooled space and the HVAC systems installed.

Initial analysis using publicly available data for 2008, suggested there was scope for DSM from heating and cooling loads in commercial offices and retail businesses. The SME portion of electric heating and cooling in commercial offices was calculated as 1760 GWh/yr. The contribution of this to peak time loads was estimated to be around 0.4 GW. There is scope for carbon reduction with motors in industry and lighting in retail and offices.

9.4 Development of a Method to Model Groups of Buildings

Objective 3:

- *To develop a method to estimate the discretionary electrical load from a group of buildings, using simulations of individual buildings*

Time profiles of electricity demand, disaggregated by end use are needed to evaluate flexible loads. A building physics approach was chosen because this accounts for each end use in a time series. The burden of data inputs was considerable and intensive to collate and check. Using data from a range of sources increased the probability of incompatibility. A limited amount of published building data was used to check the model output which confirmed that some results were outside the expected ranges. An example of this was the high annual electricity consumption for lighting in all building cases.

Age of building and HVAC type were more significant than built form type as determinants of shiftable load. The distribution of built form types was applicable at the stock level but this is no longer valid with small groups of buildings. An approach based on the quantities of actual buildings present is required due to the diversity of buildings and SME occupiers. At the scale of a DNO sub-station feeder, (category 3 in section 6.4.1), the quantity of office buildings may be such that the distribution of types is no longer valid. The external plan of each building (narrow or deep) can often be determined using aerial photography.

The external temperature had a larger impact on the power difference than the parameter variation. The use of parameters should be reviewed and expanded to account for differences in occupancy schedules and behaviour. Measured building data for validation derived from surveys of HVAC systems is needed to understand the potential for DSM in any area. There is a need to avoid synchronising the load when returning to normal operation after the DSM period as this causes a spike in demand.

9.5 Application to Office Buildings

Objective 4:

- *To apply this approach to particular building types in Reading Borough*

The simulations indicate that buildings with electric heating and cooling have the best DSM potential but this is still very small. The best DSM potential is in summer in well insulated buildings due to cooling but peak electricity demand is currently in winter. The variation in DSM due to built form type alone was small although slightly greater in open plan types. The proportion of load considered flexible during the winter was very low, with gas heating. The largest load shift during the summer was from the 1990s buildings; during the winter it was from the older buildings (1970s and 1980s).

In looking for DSM potential at the stock level, these findings indicate that an electricity company should focus on buildings with large cooling loads. These are buildings with additional cooling due to activities such as IT. Back-up power would further support DSM.

The opportunity for DSM from office buildings is small but expected to increase. Flexible HVAC load due to heating, cooling and mechanical ventilation, is present in 50 - 60% of office buildings (section 3.5.3.1). This DSM potential is increasing at an unknown rate due to refurbishment and new construction which, in some cases, adds electric heating and variable speed auxiliary systems. A building control system capable of receiving external input is necessary to interface to the smart grid. The lack of information on the type and extent of cooling and ventilation in office buildings is a major limitation.

At present, HVAC in offices has the potential to account for only a small proportion of total DSM, compared with generators (section 4.4.1). Buildings with large hot water, lighting or process loads could contribute more DSM subject to operational requirements. Generators and CHP plants will continue to be large contributors to DSM.

New electricity tariffs that will commence with smart meters will introduce SMEs to load shifting. These tariffs are expected to reflect the wholesale price of electricity which includes charges for distribution and transmission of electricity, which are significantly higher price at peak times (DUoS and TNUoS charges, section 4.2.1). This will make it possible to reduce costs without the financial penalty of agreeing to a DSM contract.

The benefits of DSM for SMEs currently appear small compared with the risks. This is especially true with STOR. HVAC systems in a large number of buildings would have to be controlled together. An aggregator company would bid volumes and prices for DSM to maximise the probability of winning a contract and minimise the risk of penalties. The contracts are complex and unfamiliar to most companies.

DNO peak load reduction requires many customers within a specific area to reduce their demand together. This could be all businesses on a business park, not just SMEs and not just office businesses.

9.6 Recommendations to Reading Borough Council

Objective 5:

- *To deliver recommendations on DSM to RBC*

Local authorities are interested in ensuring that local businesses have competitive advantage and also that they can contribute towards 2050 carbon reduction targets. Local authorities should inform businesses and landlords on smart grids and new tariffs that reflect wholesale prices. Help can be provided to access sources of information and software to convert smart grid data into information. Local authorities can educate and inform businesses on financial opportunities of smart grids, including energy saving, renewable energy and DSM. This should include examples where non-essential loads can be reduced to save money, without contracts for providing a DSM service, such as avoiding DNO 'red bands'. In order for thermal loads to be accessible for DSM, building controls and the agreement of occupiers / landlords are required. Specification of HVAC controls to interface to smart grid will be important.

Guidance for local authorities in talking to energy companies?

A local authority can work with the DNO to identify areas of peak time constraint (now and in the future). The objective of this would be to support local businesses and to encourage investment in energy efficiency by landlords and tenants. The local authority can focus information on DSM to businesses in those areas and pass on to the DNO locations where businesses are interested. The local authority and DNO can inform local businesses of the timescales for local smart grid infrastructure and potential benefits of DSM. A local authority can provide a forum for groups of SMEs and landlords to meet the DNO and facilitate co-operation.

Should local authorities engage particular types of companies or particular building types?

Businesses with generators or CHP plants are likely to be able to provide larger load reduction than companies which can only offer office cooling and auxiliary loads. Businesses with larger cooling plant than in a general office, such as IT or communications companies may be able to offer DSM. These organisations often have battery or generator back-up. Newer and refurbished buildings are more likely to have cooling and mechanical ventilation which give more flexible load. There are opportunities on business parks where building or site managers or agents could be influenced to engage in DSM across the site. In future, buildings with electric heating will present greater opportunities for load shifting during winter peak periods which would coincide with DNO peaks. If cooling demand increases, peak demand may occur more often during the summer.

9.7 Contribution

The application of a building physics model to representing DSM opportunities from a group of buildings is very sensitive to the input data. The input values need to be re-evaluated for refurbished or new buildings. An example of this is that newer lighting consumes less energy.

The use of a building physics model with a statistical overlay has demonstrated the need for better statistical data (building energy consumption data). Despite simplification, the building physics model still has a large burden of input data.

Currently there is little scope for load shifting of heating and cooling loads in offices but a small increase is expected with more cooling and electric heating. The largest DSM opportunity is currently in well insulated buildings with large cooling loads.

Built form types are a weaker indicator of DSM than age band. Building classification work points to four dominant built form types for office buildings.

RBC is recommended to focus on business parks to obtain groups of businesses for DSM, rather than SMEs directly. This points to the DNO as the customer of DSM, rather than the System Operator.

10. References

ACEEE, 2009. *Combined Heat and Power and Clean Distributed Energy Policies*, Washington DC: ACEEE.

Action Energy, 2000. *Energy Consumption Guide 19: Energy Use in Offices*, London: Action Energy.

ASHRAE, 2014. *ASHRAE Terminology List*, Atlanta, Georgia, USA: ASHRAE.

Attree, M., 2016. HVAC systems at Reading Central Library (personal communication).

Axon, C.J. et al., 2012. Building communities: reducing energy use in tenanted commercial property. *Building Resarch and Information*, 40(4), pp.461–472.

Barker, G. & Jones, M., 2013. MoU between the Local Government Association and DECC. Available at: https://www.gov.uk/sharing-information-on-greenhouse-gas-emissions-from-local-authority-own-estate-and-operations-previously-ni-185 [Accessed May 16, 2016].

BCO, 2014. *BCO Guide to Specification*, London: British Council for Offices.

BIS, 2014. *Business population estimates for the UK and regions 2014*, Sheffield: BIS. Available at: www.gov.uk/government/statistics/business-population-estimates-2014 [Accessed February 7, 2015].

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

Boyle, S., 2015. Triads: Why three is the magic number. *Connecting*. Available at: www.nationalgridconnecting.com/triads-why-three-is-the-magic-number/ [Accessed January 5, 2016].

Bradford, J. & Fraser, E., 2008. Local Authorities, Climate Change and Small and Medium Enterprises: Identifying Effective Policy Instruments to Reduce Energy Use and Carbon Emissions. *Corporate Social Responsibility and Environmental Management*, 15(3), pp.156–172.

Braun, J., 2003. Load Control Using Building Thermal Mass. *Journal of Solar Energy Engineering*, 125, pp.292–301.

BRE, 2014a. *A Technical Manual for SBEM*, London: DCLG.

BRE, 2014b. *National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in England)* 2013th ed., Watford: BRE.

British Property Federation, 2014. *Property Data Report 2014*, London: BPF.

Brown, F. et al., 2000. Surveys of nondomestic buildings in four English towns. *Environment and Planning B: Planning & Design*, 27, pp.11–24.

Brown, R. et al., 2008. *Report to Congress on Server and Data Center Energy Efficiency: Public Law 109-431*, Berkley, California: Lawerence Berkley National Laboratory.

Bruhns, H., 2000. Property taxation data for non domestic buildings in England and Wales. *Environment and Planning B: Planning & Design*, 27, pp.33–49.

Bruhns, H. et al., 2000. Types, numbers, and floor areas of non domestic premises in England and Wales, classified by activity. *Environment and Planning B: Planning & Design*, 27, pp.641–666.

Bruhns, H., Steadman, P. & Marjanovic, L., 2006. A Preliminary Model of Non-Domestic Energy for England and Wales. In E. Sivyer, ed. *The Annual Research Conference of the Royal Institution of Chartered Surveyors (COBRA) Conference*. London: RICS.

Bruhns, H. & Wyatt, P., 2011. A data framework for measuring the energy consumption of the non-domestic building stock. *Building Research & Information*, 39(3), pp.211–226.

BSI, 2010. *BS EN 50160: Voltage characteristics of electricity supplied by public electricity networks*, London: BSI.

BSI, 2013. Part 1: Terms, definitions and classification. In *Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling*. London: BSI.

BusinessLink, 2006. Fuel, Energy and Water Costs. *South East Business Monitor*, (2), p.12.

Caeiro, J. et al., 2008. Using street surveys to establish Air Conditioning incidence in UK's commercial offices stock. In *IEECB'08, Improving Energy Efficiency in Commercial Buildings Conference*. Frankfurt.

Carbon Trust, 2009. *Building the Future, Today*, London: The Carbon Trust.

Carbon Trust, 2014. *Motors and drives*, London: Carbon Trust.

Centre for Cities, 2014. *Small Business Outlook 2014*, London: Centre for Cities.

Churcher, D., 2014. *Life Cycle Assessment: An assessment of a building services system*, Bracknell: BSRIA.

CIBSE, 2015. *CIBSE Guide A: Environmental Design* 8th ed. D. Braham, ed., London: CIBSE.

CIBSE, 2005. *CIBSE Guide B: Heating, ventilating, air conditioning and refrigeration*,

London: CIBSE.
CIBSE, 2012. *CIBSE Guide F: Energy efficiency in buildings* 3rd ed., London: CIBSE.
Clevenger, C.M., Haymaker, J.R. & Jalili, M., 2014. Demonstrating the Impact of the Occupant on Building Performance. *Journal of Computing in Civil Engineering*, 28(February), pp.99–102.
Committee on Climate Change, 2010. Progress Reducing Emissions from Buildings and Industry. In *Meeting Carbon Budgets – ensuring a low-carbon recovery*. London: Committee on Climate Change, p. 28.
Connell, N., 2007. *Social and Environmental Responsibility and the Small Business Owner*, London: Federation of Small Businesses.
Crawley, D. et al., 2005. *Contrasting the Capabilities of Building Energy Performance Simulation Programs*, US Department of Energy.
Crawley, D. et al., 2001. EnergyPlus: Creating a new-generation building energy simulation program. *Energy and Buildings*, 33(4), pp.319–331.
Crawley, D.B., 1998. Which Weather Data Should You Use for Energy Simulations of Commercial Buildings? *Ashrae Transactions*, 104(2), pp.1–18.
Darby, S., 2010. Smart metering: what potential for householder engagement? *Building Research & Information*, 38(5), pp.442–457.
data.gov.uk, 2014. New suggested definition for “Disclosive” made by exstat. Available at: https://data.gov.uk/new-suggested-definition-disclosive-made-exstat [Accessed May 16, 2016].
DCLG, 2012. *Improving the energy efficiency of our buildings*, London: Department for Communities and Local Government.
DCLG, 2006. *Non-domestic Heating, Cooling and Ventilation Compliance Guide* 1st ed., London: RIBA Enterprises Ltd.
DECC, 2014a. Become a Green Deal business. Available at: www.gov.uk/become-green-deal-business [Accessed May 16, 2016].
DECC, 2014b. *D3: Opportunities for integrating demand side energy policies*, London: DECC.
DECC, 2013a. *DECC Non-domestic building energy use project phase I*, London: DECC.
DECC, 2011a. Electricity. In *Digest of United Kingdom Energy Statistics*. London: DECC.
DECC, 2014c. *Energy Consumption in the UK*, London: DECC.
DECC, 2010. *Energy Consumption in the UK - A User Guide* 1.1 ed., London: DECC.

DECC, 2012. *Energy Consumption in the UK: Service Sector data tables. 2012 update*, London: DECC.

DECC, 2015. Energy Technology List (ETL). Available at: www.eca.gov.uk [Accessed May 16, 2016].

DECC, 2014d. *Gas and electricity prices in the non-domestic sector*, London: DECC. Available at: https://www.gov.uk/government/statistical-data-sets/gas-and-electricity-prices-in-the-non-domestic-sector [Accessed May 16, 2016].

DECC, 2014e. *Smart meter rollout for the domestic and small and medium non-domestic sectors (GB): Impact Assessment*, London.

DECC, 2011b. Smart meter Rollout for the Small and Medium Non-domestic Sector: Impact Assessment.

DECC, 2014f. *Smart Metering Implementation Programme Smart Metering Equipment Technical Specifications Version 1.58*, London: DECC.

DECC, 2013b. *Smart Metering Implementation Programme: Non-domestic smart metering: Q&A* 2nd ed., London: DECC.

DECC, 2011c. *Smart Metering Implementation Programme: Overview Document*, London: DECC.

DECC, 2014g. *Smart Metering Implementation Programme: Third Annual Report on the Roll-out of Smart Meters*, London.

DECC, 2014h. *Sub-national consumption statistics: Methodology and guidance booklet*, London: DECC.

DECC, 2011d. *The Green Deal*, London: DECC.

DECC, 2009. *The UK Renewable Energy Strategy* 1st ed., London: TSO.

DECC & Ofgem, 2014. *Statutory Security of Supply Report 2014*, London: HM Government.

Defra, 2010. *Central Air Conditioning Plant, Government Standards Evidence Base 2009: Key Inputs* 1.1 ed., London: Defra.

Defra, 2006. *Policy Options to Encourage Energy Efficiency in the SME and Public Sectors*, London: Defra.

DesignBuilder, 2011. *DesignBuilder EnergyPlus Simulation Documentation for DesignBuilder v3.0*, Stroud, Gloucs: DesignBuilder.

DesignBuilder, DesignBuilder Simulation. Available at: www.designbuilder.co.uk [Accessed May 16, 2016].

DEWO, 1995. Part L1: Conservation of Fuel and Power. In *The Building Regulations 1991*. London: DEWO.

DEWO, 1990. *The Building Regulations - Approved Document L: conservation of Fuel and Power*, London: Department of the Environment and the Welsh Office.

Dieckmann, J., Roth, K. & Brodrick, J., 2007. Dedicated Outdoor Air systems Revisited. *Ashrae Journal*, (December), pp.127–129.

Dolman, M. et al., 2012. *Demand side Response in the non-domestic sector*, London: Ofgem.

DTI, 2002. *Energy Consumption in the United Kingdom*, London: DTI.

DTLR, 2002. Part L2: Conservation of fuel and power in buildings other than dwellings. In *The Building Regulations 2000*. London: Department of Transport Local Government and the Regions.

Elexon, 2008. *BSCP516: Allocation of Profile Classes & SSCs for Non-half hourly SVA Metering Systems Registered in SMRS* 7th ed., London, UK: Elexon. Available at: www.elexon.co.uk [Accessed May 16, 2016].

Elexon, 2014. *Definitions of seasons and day types* v1.0 ed., London: Elexon.

Elexon, 2013a. *Load Profiles and their use in Electricity Settlement* 2nd ed., London: Elexon. Available at: www.elexon.co.uk/reference/technical-operations/profiling/ [Accessed April 28, 2016].

Elexon, 2013b. *The Electricity Trading Arrangements: A beginner's guide* 4th ed., London: Elexon.

Energy UK, 2015. The energy market explained. Available at: www.energy-uk.org.uk/energy-industry/the-energy-market.html [Accessed May 16, 2016].

EnergyPlus, 2012a. *Auxiliary EnergyPlus Programs*, Washington DC: US Department of Energy.

EnergyPlus, 2012b. *EnergyPlus Engineering Reference*, Washington DC: US Department of Energy.

EnergyPlus, 2012c. *Input Output Reference*, Washington DC: US Department of Energy.

EPSRC, 2014. *Clarifications of EPSRC expectations on research data management*, Swindon: EPSRC. Available at: www.epsrc.ac.uk/about/standards/researchdata/expectations/ [Accessed May 16, 2016].

Esri, ArcGIS Platform. Available at: www.esri.com/software/arcgis [Accessed May 16, 2016].

European Commission, 2003. Commission Recommendation concerning the definition of micro, small and medium-sized enterprises. *Official Journal of the European Union*, pp.36–41.

European Commission, 2013. FAQs about ETP Smart Grids. Available at: www.smartgrids.eu/FAQ#12 [Accessed May 16, 2016].

European Parliament, 2010. *Directive 2010/75/EU of the European Parliament and of the Council on Industrial Emissions (integrated pollution prevention and control)*, EU.

European Parliament, 2001. *Large Combustion Plants Directive*, Brussels, Belgium: European Commission.

Evans, G. & Bessant, N., 2014. *New Thames Valley Vision. Knowledge Sharing Report: Overall Proven Benefits*, Reading: SSEPD.

Fawcett, J., 2010. *Department of Energy and Climate Change: Unconstrained Sector Research*, Birmingham: Databuild.

Field, J. et al., 2008. *Energy benchmarks*, London: CIBSE.

Flexitricity, 2015. *Demand Response. Delivered: Service Overview*, Edinburgh: Flexitricity.

Forster, D. et al., 2010. *Assessing the carbon dioxide emissions and cost-effective carbon savings potential for organisations not covered by EU ETS, CCAs or CRC (CESA 0903)*, Harwell: AEA.

Frontier Economics, 2015. *Insight Report: Small and Medium Enterprises (SMEs): Disaggregated Load, Time of Use Tariff and Restricted Hours Trials*, Newcastle Upon Tyne: Northern Powergrid.

Futcher, J. & Mills, G., 2013. The role of urban form as an energy management parameter. *Energy Policy*, 53, pp.218–228.

Gellings, C., 1985. The concept of demand-side management for electric utilities. *Proceedings of the IEEE*, 73(10), pp.1468–1470.

Gellings, C., 1996. Then and now: The perspective of the man who coined the term “DSM.” *Energy Policy*, 24(4), pp.285–288.

Goodright, V., 2015. Service Sector: Breakdown by end uses in ECUK 2014 (personal e-mail).

Google, 2015. Google Maps. Available at: www.maps.google.co.uk/maps [Accessed May 16, 2016].

Government Office for Science, 2008. *Powering our Lives: Sustainable Energy Management and the Built Environment*, London.

Greenberg, S., Mills, E. & Tschudi, W., 2006. Best Practices for Data Centers: Lessons Learned from Benchmarking 22 Data Centers. In *2006 ACEEE Summer Study on Energy Efficiency in Buildings*. pp. 76–87.

Grünewald, P. & Torriti, J., 2013. Demand response from the non-domestic sector: Early UK experiences and future opportunities. *Energy Policy*, 61, pp.423–429.

Hawkes, A.D., 2010. Estimating marginal CO2 emissions rates for national electricity systems. *Energy Policy*, 38(10), pp.5977–5987.

Hawkins, G., 2011. *Rules of Thumb: Guidelines for building services* 5th ed., Bracknell: BSRIA.

Hay, R. & Macwhinnie, N., 2015. *Making the electricity system more flexible and delivering the benefits for consumers: Position paper*, London: Ofgem.

Heiple, S. & Sailor, D.J., 2008. Using building energy simulation and geospatial modeling techniques to determine high resolution building sector energy consumption profiles. *Energy and Buildings*, 40(8), pp.1426–1436.

Herter, K., 2007. Residential implementation of critical-peak pricing of electricity. *Energy Policy*, 35, pp.2121–2130.

Hinnells, M., 2008. Technologies to achieve demand reduction and microgeneration. *Energy Policy*, 36, pp.4427–4433.

Hitchin, E. & Pout, C., 2000. Local Cooling: Global Warming? UK Carbon Emissions from Air-Conditioning in the Next Two Decades. In *CIBSE Conference Conference*. Dublin: CIBSE.

HM Government, 2010a. Approved Document F: Means of Ventilation. In *The Building Regulations 2010*. London: HM Government.

HM Government, 2010b. *Non-Domestic Building Services Compliance Guide*, London: RIBA Enterprises Ltd.

HM Government, 2014. *Non-Domestic Building Services Compliance Guide* 2013th ed., London: RIBA Enterprises Ltd.

HM Government, 2010c. Part L2A: Conservation of Fuel and Power in New Buildings Other than Dwellings. In *The Building Regulations 2010*. London: HM Government.

HM Government, 2007. The Energy Performance of Buildings (Certificates and Inspections) (England and Wales) Regulations (SI No. 991).

HMRC, 2014. Excise Notice CCL1: a general guide to Climate Change Levy.

Hong, S. & Steadman, P., 2013. *An Analysis of Display Energy Certificates for Public Buildings, 2008 to 2012*, London: CIBSE. Available at: www.bartlett.ucl.ac.uk/energy/news/display-energy-certificates [Accessed May 16, 2016].

HSE, 2013. *Workplace health, safety and welfare: Approved Code of Practice and guidance* 2nd ed., London.

Ingersoll-Rand, 2013. *Trane (TM) Dedicated Outdoor Air Systems*, Ingersoll Rand.

Int-Hout, D. & Wilbar, L., 2014. Variable Volume DOAS Fan-Powered Terminal Unit. *ASHRAE Journal*, August, pp.70–73.

J Mould, 2014. Local Demolition Firm to Demolish Iconic Metal Box Building in Reading Town Centre. Available at: http://jmouldreading.co.uk/news/local-demolition-firm-demolish-iconic-metal-box-building-reading-town-centre/ [Accessed May 16, 2016].

Jeffries, I., Rowlands-Rees, T. & Rogers, W., 2015. *Energy Efficiency Trends Volume 9*, London: Green Investment Bank. Available at: www.greeninvestmentbank.com [Accessed May 16, 2016].

Jenkins, D., Banfill, P. & Pellegrini-Masini, G., 2009. *Non-domestic conclusions of the Tarbase project–Reducing CO2 emissions of existing buildings*, Edinburgh: Heriot-Watt University.

Jenkins, D. & Newborough, M., 2007. An approach for estimating the carbon emissions associated with office lighting with a daylight contribution. *Applied Energy*, 84(6), pp.608–622.

Jewell, P., 2014. *Developing Future Power Networks: Introducing Project Falcon*, Bristol: Western Power Distribution.

Jones, P., Patterson, J. & Lannon, S., 2007. Modelling the built environment at an urban scale—Energy and health impacts in relation to housing. *Landscape and Urban Planning*, 83(1), pp.39–49.

Kavgic, M. et al., 2010. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and Environment*, 45(7), pp.1683–1697.

Khan, S. & Stadnyk, S., 2013. *Areas and types of properties off the gas grid*, London: DECC.

KiWi Power, 2014. Frequently Asked Questions. Available at:

www.kiwipowered.com/about/faq [Accessed January 5, 2016].
KiWi Power, Powering innovation in energy technology (factsheet). Available at: www.kiwipowered.com/innovation [Accessed May 9, 2016].
Knight Frank, Bray Fox Smith & Haslams, 2014. The Blade: Floorplans. Available at: www.thebladereading.com/downloads.aspx [Accessed May 16, 2016].
Korolija, I. et al., 2011. Influence of building parameters and HVAC systems coupling on building energy performance. *Energy and Buildings*, 43(6), pp.1247–1253.
Korolija, I. et al., 2013. UK office buildings archetypal model as methodological approach in development of regression models for predicting building energy consumption from heating and cooling demands. *Energy and Buildings*, 60, pp.152–162.
Kossecka, E. & Kosny, J., 2002. Influence of insulation configuration on heating and cooling loads in a continuously used building. *Energy and Buildings*, 34, pp.321–331.
Lloyds Bank, 2010. *Small Businesses Suffering "Environmental Inertia",* London: Lloyds TSB Bank plc.
Lomas, K.J. et al., 2011. The Carbon Footprint of UK Cities 4M: measurement, modelling, mapping and management. *ISOCARP Review 06 International Society of City and Regional Planners*.
MacKenzie, F. et al., 2010. *Energy Efficiency in new and Existing Buildings: Comparative Costs and CO2 Savings*,
MacLeay, I., Harris, K. & Annut, A., 2014. *Digest of United Kingdom Energy Statistics (DUKES) 2014*, London: DECC.
Markit Economics, 2013. *Tech Monitor UK*, London: KPMG. Available at: www.kpmg.com/uk/techmonitoruk [Accessed May 16, 2016].
Mathworks, Quantiles and Percentiles. Available at: http://uk.mathworks.com/help/stats/quantiles-and-percentiles.html [Accessed May 16, 2016].
Matlab, Matlab: Overview. Available at: www.mathworks.co.uk/products/matlab [Accessed May 16, 2016].
Menezes, A. et al., 2014. Estimating the energy consumption and power demand of small power equipment in office buildings. *Energy and Buildings*, 75, pp.199–209.
Mortimer, N.D., Ashley, A. & Rix, J.H.R., 2000. Detailed energy surveys of nondomestic buildings. *Environment and Planning B: Planning and Design*, 27, pp.25–32.
Motegi, N. et al., 2007. *Introduction to Commercial Building Control Strategies and*

Techniques for Demand Response, Berkley, California: California Energy Commission.

National Audit Office, 2007. *The Carbon Trust Accelerating the Move to a Low Carbon Economy*, London: NAO. Available at: www.nao.org.uk [Accessed May 16, 2016].

National Grid, 2009. *Ancillary Service Settlement Guide: Short Term Operating Reserve*, Warwick: National Grid.

National Grid, Electricity. Available at: www2.nationalgrid.com/About-us/What-we-do/Electricity/ [Accessed May 16, 2016a].

National Grid, Electricity System Operator Incentives. Available at: www2.nationalgrid.com/UK/Industry-information/Electricity-system-operator-incentives/Incentives/ [Accessed May 16, 2016b].

National Grid, 2014a. *Frequently Asked Questions: Demand Side Balancing Reserve*, Warwick: National Grid.

National Grid, 2015a. *Future Energy Scenarios*, Warwick: National Grid.

National Grid, Keeping the Electricity Transmission System in balance. Available at: www2.nationalgrid.com/uk/services/balancing-services/ [Accessed May 5, 2016c].

National Grid, 2011. *Operating the Electricity Transmission Operating Networks in 2020*, National Grid.

National Grid, 2013a. *Short Term Operating Reserve (STOR) Tender Assessment Principles*, Warwick: National Grid.

National Grid, 2013b. *Short Term Operating Reserve Annual Market Report 2012 / 13*, Warwick: National Grid.

National Grid, 2015b. *Short Term Operating Reserve: Fuel type analysis - Season 8.3*, Warwick: National Grid.

National Grid, 2015c. *Short Term Operating Reserve: Fuel type analysis - Season 8.5*, Warwick: National Grid.

National Grid, 2014b. *Short Term Operating Reserve: General Description of the Service*, Warwick: National Grid.

National Grid, 2014c. *STOR Market Information Report: Tender Round 23*, Warwick: National Grid.

National Grid, Transmission Network Use of System Charges. Available at: www2.nationalgrid.com/UK/Industry-information/System-charges/Electricity-transmission/Transmission-network-use-of-system-charges/ [Accessed January 6, 2016d].

National Grid, 2016. *Triad Data*, Warwick: National Grid.

National Grid, 2014d. *Triad data*, National Grid. Available at: http://www2.nationalgrid.com/UK/Industry-information/System-charges/Electricity-transmission/Transmission-Network-Use-of-System-Charges/Transmission-Charges-Triad-Data/ [Accessed May 16, 2016].

National Grid, What we do in the Electricity Industry. Available at: www2.nationalgrid.com/uk/our-company/electricity [Accessed May 16, 2016e].

Neffendorf, H., Bruhns, H. & Harrison, A., 2009. *Non-domestic Energy Efficiency Data Framework (NEED): Scoping Study Findings*, London: DECC.

Nord Pool Spot, 2016. N2EX Day Ahead Auction Prices. Available at: http://www.nordpoolspot.com/Market-data1/N2EX/Auction-prices/UK/Hourly/?view=chart [Accessed January 5, 2016].

O'Connor, J., 2004. Survey on actual service lives for North American buildings. In *Woodframe Housing Durability and Disaster Issues*. Las Vegas, pp. 1–9.

ODPM, 2005. Age of Commercial and Industrial Stock: Local Authority Level 2004.

ODPM, 2006. Part L2A: Conservation of Fuel and Power in New Buildings Other than Dwellings. In *The Building Regulations 2000*. London: Office of the Deputy Prime Minister.

Office for National Statistics, 2015. Population estimates. Available at: www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/popuationestimates [Accessed May 12, 2016].

OfficeBroker, 2014. *UK Rental Rates Guide*, London: OfficeBroker. Available at: www.officebroker.com/knowledge-centre [Accessed May 16, 2016].

Ofgem, 2015a. Cheaper off-peak electricity for business consumers. *Factsheet 131*. Available at: www.ofgem.gov.uk [Accessed May 16, 2016].

Ofgem, 2015b. Independent Distribution Network Operators. Available at: www.ofgem.gov.uk/electricity/distribution-networks/connections-and-competition/independent-distribution-network-operators [Accessed May 16, 2016].

Ofgem, 2016a. Low Carbon Networks Fund. Available at: https://www.ofgem.gov.uk/electricity/distribution-networks/network-innovation/low-carbon-networks-fund [Accessed May 16, 2016].

Ofgem, 2014. Suppliers' advanced meter roll-out performance. Available at:

www.ofgem.gov.uk [Accessed May 16, 2016].

Ofgem, 2016b. The GB electricity distribution network. Available at: www.ofgem.gov.uk/electricity/distribution-networks/gb-electricity-distribution-network [Accessed May 16, 2016].

Open Energi, 2015a. University of East Anglia helps to keep the lights on with Dynamic Demand. Available at: www.openenergi.com/our-customers/university-of-east-anglia/ [Accessed May 2, 2016].

Open Energi, 2015b. What is Dynamic Demand? Available at: www.openenergi.com/our-technology [Accessed April 25, 2016].

Parekh, A., 2005. Development of Archetypes of Building Characteristics Libraries for Simplified Energy Use Evaluation of Houses. In *Ninth International IBPSA Conference*. Montréal, Canada: IBPSA, pp. 921–928.

Parliament, 1965. Part F: Thermal Insulation. In *The Building Regulations, SI No. 1373*. London: HMSO, pp. 52–53.

Parliament, 1972. Part F: Thermal Insulation. In *The Building Regulations, SI No. 317*. London: HMSO, pp. 61–63.

Parliament, 1976. Part F: Thermal Insulation. In *The Building Regulations, SI No. 1676*. London: HMSO, pp. 4305–4307.

Parliament, 1985. Part L: Conservation of Fuel and Power. In *The Building Regulations, SI No. 1065*. London: HMSO, pp. 3412–3416.

Parliament, 1967. Schedule 115: Interpretation. In *The General Rate Act*. London.

Parliament, 1988a. Schedule 5: Non-domestic Rating Exemption. In *Local Government Finance Act*. London.

Parliament, 1988b. Section 64: Hereditaments. In *Local Government Finance Act*. London.

Parliament, 2002. *The Electricity Safety, Quality and Continuity Regulations 2002*, London.

Pearsall, J. et al. eds., 1999. *Concise Oxford Dictionary* 10th ed., Oxford: OUP.

Perez-Lombard, L., Ortiz, J. & Pout, C., 2008. A review on buildings energy consumption information. *Energy*, 40, pp.394–398.

Pinsent Masons, 2012. The Pinsent Masons Sustainability and Energy Toolkit: The Development of Green Leases. Available at: www.pinsentmasons.com [Accessed November 9, 2015].

Pout, C., 2000. N-DEEM: The National Nondomestic Buildings Energy and Emissions Model. *Environment and Planning B: Planning & Design*, 27, pp.721 – 732.

Pout, C., Mackenzie, F. & Bettle, R., 2002. *Carbon dioxide emissions from non-domestic buildings: 2000 and beyond*, Watford: BRE.

Pout, C., Moss, S. & Davidson, P., 1998. *Non-domestic Building Energy Fact File*, London: Department of the Environment, Transport and the Regions.

Ravetz, J., 2008. State of the stock — What do we know about existing buildings and their future prospects? *Energy Policy*, 36, pp.4462–4470.

RCCP, 2013a. *Reading Means Business on Climate Change: Reading's Climate Change Strategy 2013-2020*, Reading: Reading Climate Change Partnership.

RCCP, 2013b. *Reading Means Business on Climate Change: Theme Action Plans*, Reading: Reading Climate Change Partnership.

Rickaby, P.A. & Gorgolewski, M.T., 2000. A classification system for services in nondomestic buildings. *Environment and Planning B: Planning and Design*, 27, pp.695–708.

Ruseva, V., 2014. *Home Business Report*, London: Enterprise Nation. Available at: https://www.enterprisenation.com/homebusiness [Accessed May 16, 2016].

Salat, S., 2009. Energy loads, CO2 emissions and building stocks: morphologies, typologies, energy systems and behaviour. *Building Research & Information*, 37(5-6), pp.598–609.

Savills & Strutt & Parker, 2014. All Change for Reading: Station Hill. Available at: www.stationhillreading.co.uk/development/downloads/ [Accessed May 16, 2016].

Scrase, J.I., 2001. Curbing the growth in UK commercial energy consumption. *Building Research & Information*, 29(1), pp.51–61.

Seem, J., 1987. *Modeling of Heat Transfer in Buildings*. University of Wisconsin-Madison.

Shahrestani, M., 2013. *Multiple attribute decision making for HVAC&R systems selection, PhD thesis*. University of Reading.

Shahrestani, M., Yao, R. & Cook, G.K., 2013. Characterising the energy performance of centralised HVAC & R systems in the UK. *Energy & Buildings*, 62, pp.239–247.

Sidebotham, E., 2015. *Customer led network revolution Project Close down report*, Newcastle Upon Tyne: Northern Powergrid.

Spitler, J., 2011. Thermal load and energy performance prediction. In J. Hensen & R. Lamberts, eds. *Building Performance Simulation for Design and Operation*. Abingdon, Oxon: Spon Press.

SSEPD, 2012a. *New Thames Valley Vision Customer Engagement Plan for Relevant*

Customers, Reading: SSEPD. Available at: www.thamesvalleyvision.co.uk/get-involved/.

SSEPD, 2014. *Southern Electric Power Distribution plc: Use of System Charging Statement* 1.1 ed., Reading: SSEPD.

SSEPD, 2012b. Thames Valley Vision. Available at: www.thamesvalleyvision.co.uk/ [Accessed May 16, 2016].

Stannard, M., 2013. *New Thames Valley Vision Customer Engagement Lessons Learnt*, SSEPD.

Stannard, M. & Hewitt, G., 2014. *Demand Side Response Evaluation & Network Controlled Demand Side Response & Energy Efficiency*, Reading: SSEPD.

Steadman, P., Bruhns, H., Holtier, S., et al., 2000. A Classification of Built Forms. *Environment and Planning B: Planning and Design*, 27, pp.73–91.

Steadman, P., Bruhns, H. & Rickaby, P., 2000. An Introduction to the National Non-Domestic Building Stock Database. *Environment and Planning B: Planning & Design*, 27, pp.3–10.

Strbac, G. et al., 2010. *Benefits of Advanced Smart Metering for Demand Response based Control of Distribution Networks* 2nd ed., London: SEDG & ENA.

Strbac, G., 2008. Demand side management: Benefits and challenges. *Energy Policy*, 36, pp.4419–4426.

Swan, L.G. & Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13(8), pp.1819–1835.

Swandells, G., 2014. *Falcon Commercial Trials Season 1 - Winter 2013/14*, Bristol: Western Power Distribution.

Thames Valley Berkshire, 2014. *Thames Valley Berkshire: Delivering national growth, locally: Evidence Base*, Reading: Thames Valley Berkshire LEP. Available at: http://thamesvalleyberkshire.co.uk/Data-Research [Accessed May 16, 2016].

Thames Valley Vision, 2012. Our project: What are we doing? Available at: www.thamesvalleyvision.co.uk/our-project/ [Accessed May 16, 2016].

Tian, W. & Choudhary, R., 2012. A probabilistic energy model for non-domestic building sectors applied to analysis of school buildings in greater London. *Energy and Buildings*, 54, pp.1–11.

UEA, 2014. Dynamic Demand: Green Gown Awards 2014: Highly Commended.

Available at: www.uea.ac.uk/about/sustainability/case-studies/dynamic-demand [Accessed May 2, 2016].

UK Green Building Council, 2007. *Report on carbon reductions in new non-domestic buildings*, London: Department for Communities and Local Government.

US Department of Energy, 2015. EnergyPlus Energy Simulation Software. Available at: https://energyplus.net [Accessed May 16, 2016].

US Department of Energy, 2011. EnergyPlus: Research Papers and Articles. Available at: http://apps1.eere.energy.gov/buildings/energyplus/energyplus_research.cfm [Accessed March 25, 2015].

US Department of Energy, 2014. EnergyPlus: Testing and Validation. Available at: https://energyplus.net/testing [Accessed May 16, 2016].

Vickers, I. & Vaze, P., 2009. *SMEs in a Low Carbon Economy*, London: BERR.

VOA, 2012a. Business Floorspace (Experimental Statistics). Available at: https://www.gov.uk/government/statistics/business-floorspace-experimental-statisticsl [Accessed May 16, 2016].

VOA, 2012b. *Business Floorspace (Experimental Statistics): Release Notes*, London: VOA. Available at: https://www.gov.uk/government/statistics/business-floorspace-experimental-statistics [Accessed May 16, 2016].

VOA, 2016. Business rates: how different properties are measured. Available at: https://www.gov.uk/guidance/measuring-property-for-rating-purposes [Accessed May 16, 2016].

VOA, 2010a. Glossary page. Available at: www.2010.voa.gov.uk/rli/static/HelpPages/English/glossary/index.html [Accessed May 16, 2016].

VOA, 2006. Volume 4, Section 2: Occupation and the Hereditament. In *Rating Manual*. London. Available at: http://manuals.voa.gov.uk/corporate/publications/Manuals/RatingManual/RatingManualVolume4/sect2/part1/a-rat-man-vol4-s2-pta.html#TopOfPage [Accessed May 16, 2016].

VOA, 2010b. What business/non-domestic property qualifies as exempt from business rates? Available at: www.2010.voa.gov.uk/rli/static/HelpPages/English/faqs/faq152-businesses_exemp_from_rates.html [Accessed May 16, 2016].

Ward, J., Pooley, M. & Owen, G., 2012. *What Demand-Side Services Can Provide Value* *to the Electricity Sector? Paper 4*, London: Sustainability First.

White, S., 2014. *Business Population Estimates for the UK and Regions 2014*, Sheffield: BIS.

Wood, F. & Caro, D., 2010. *Making Sense of Going Green*, London: Federation of Small Businesses.

Worringham, M., 2004. *ELR Database of Sites*, Reading Borough Council (unpublished).

Wright, A., 2005. Development of a Building Energy Model for Carbon Reduction in the UK Non-domestic Stock. In *9th International IBPSA Conference*. Montréal, Canada: IBPSA, pp. 1355–1360.

Yamaguchi, Y., Shimoda, Y. & Mizuno, M., 2007. Proposal of a modeling approach considering urban form for evaluation of city level energy management. *Energy and Buildings*, 39(5), pp.580–592.

Yao, R. & Steemers, K., 2013. Urban microclimates and simulation. In R. Yao, ed. *Design and Management of Sustainable Built Environments*. London: Springer, p. 81.

Zhang, Y. & Korolija, I., 2014. JEPlus – An EnergyPlus simulation manager for parametrics. Available at: www.jeplus.org [Accessed May 16, 2016].

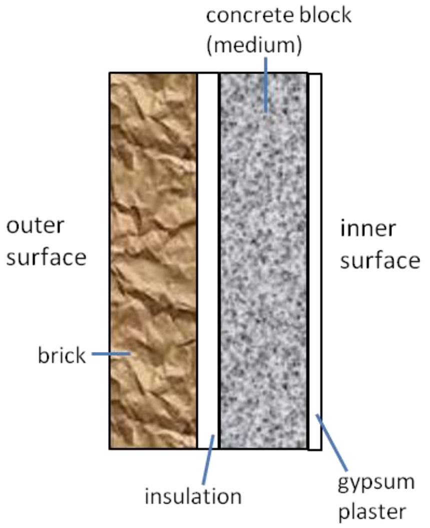
Zhao, H. & Magoulès, F., 2012. A review on the prediction of building energy consumption. *Renewable and Sustainable Energy Reviews*, 16(6), pp.3586–3592.

Appendix A

Construction of modelled building elements

The construction of building thermal elements are detailed in tables 49 to 51 below.

Table 64 External wall: material dimensions

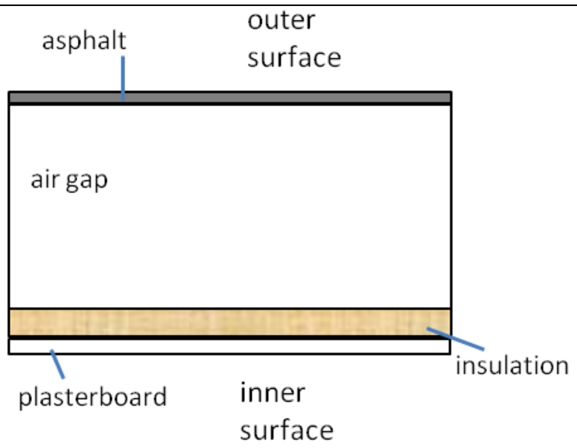


	1970	1980	1990
Thickness of building materials (mm)			
brick	100	100	100
XPS extruded polystyrene	5	25 *	60
concrete block (medium)	100	100	100
gypsum plaster	13	13	13

* glass fibre quilt

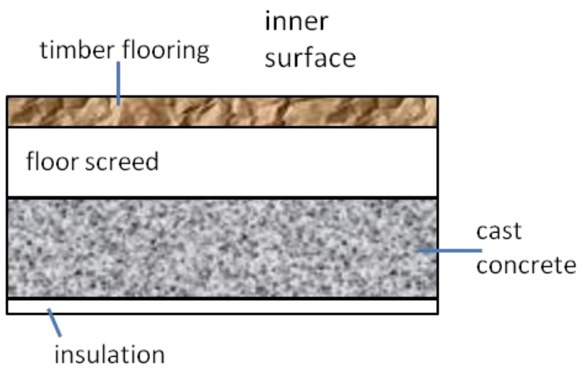
Table 64 illustrates the external wall construction used in the model. The adjacency of the materials is the same for all three age bands. Table 64 gives the dimensions for each material. The thickness of insulation is increased in the newer buildings to give lower U-values.

Table 65 Roof construction: material dimensions



	1970	1980	1990
Thickness of building materials (mm)			
asphalt	10	10	10
air gap	200	200	200
glass fibre quilt	-	63	100
plasterboard	13	13	13

Table 66 Ground floor: material dimensions



	1970	1980	1990
Thickness of building materials (mm)			
timber flooring	30	30	30
floor screed	70	70	70
cast concrete	100	100	100
urea formaldehyde foam	10	25 *	75
* glass fibre quilt			