Electricity Demand: Measurement, modelling and management of UK homes

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Declaration of Originality

I Mark Julian Bilton declare that this thesis is all my own work with the exception of that which is appropriately referenced.
Abstract

The need to achieve a transition to a low carbon economy has renewed interest in ‘energy efficiency’ and what has become known as ‘demand side management’. This thesis investigates the role of measurement and modelling in the management of domestic electricity demand. Practice and policy have, since the 1950s, tended to favour a ‘supply paradigm’ centred on the imperative of increasing energy supply. Despite the upheaval of market liberalisation, and twenty years of climate change debate, the domestic electricity ‘culture’ has changed very little. The first half of this thesis contributes to this subject by describing the complex development of the electricity system that we are familiar with today. Drawing upon technical, social and political themes, the current and emerging practices of measurement, modelling, and management are critiqued. It is argued that current practices require revaluation, if alternative, decentralised approaches are to receive a fair analysis. The thesis contributes in empirical terms by extending the evidence base and developing modelling tools for the analysis of domestic electricity use. Field data collected by the author concerning the power flow characteristics of domestic appliances are presented which identify the dynamic nature of domestic electrical loads. A modelling framework is then introduced that combines social and technical aspects of domestic energy demand, allowing synthesis of domestic load profiles and allowing comparison between localised interventions.
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‘The art of measurement, by showing us the truth would have brought our soul into the repose of abiding by the truth, and so would have saved our life.’

Protagoras
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1 Introduction

In the first decade of the twenty first century the issue of anthropogenic climate change moved from being a fringe concern to become a mainstream political issue (IPCC 2007; UNEP 2007; DECC 2009). The International Panel on Climate Change’s (IPCC) fourth assessment report, published in 2007, stated that climate change was ‘unequivocal’ and ‘with very high confidence’ that human activities through the burning of fossil fuel, and land use change, are causing an increase in global temperatures (IPCC 2007). Anthropogenic climate change\(^1\) is caused by a range of greenhouse gases (GHG), with carbon dioxide (CO\(_2\)), released as a by-product of mankind’s energy systems, constituting the largest single source. Consequently, climate change mitigation now frames the governance of energy use in the industrial, commercial, domestic and transport sectors (DECC 2009). As the evidence for climate change has improved, estimates of the scale the emission reductions required to avert serious consequences have increased. For example the UK’s 2050 target shifted from 60\% in 2007 (HMG 2007) to 80\% in 2008 (HMG 2008). These targets represent an unprecedented challenge given that western societies and their electrical systems have co-evolved for over a century, and are now deeply intermeshed.

The majority of carbon emissions associated with industry and transport are caused by the direct burning of fuels. However the production of electricity, which is used to some extent by all sectors, is the largest single cause of the UK’s emissions, representing around one third of the total. The policy discourse surrounding electricity related carbon emissions is one contributed to by a number of groups, each advocating different approaches to abatement and conservation. In the UK, renewable energy, and most notably wind power, has moved from being ‘alternative energy’ to a mainstream technology, supported through government legislation (HMG 2009). After decades of decline and unpopularity, nuclear power is now experiencing a renaissance\(^2\) with renewed support from government (DECC 2009) and environmentalists such as James Lovelock (Lovelock 2004). Advocates of carbon

\(^1\)The term anthropogenic refers to changes caused by human activity.

\(^2\)Many nuclear plants where cancelled in the early 1970s because of ‘economic recession, rising capital and fuel costs and environmental concerns’ IAEA (2004). 50 Years of Nuclear Energy.
Capture and storage (CSS) propose that fossil fuel power stations can contribute to a low carbon energy mix by pumping carbon emissions underground (CCSa 2009). These approaches entail the substitution or modification of existing power station technology, and as such do not challenge what has become known as the centralised or ‘supply paradigm’ (Bouffard and Kirschen 2008), where electrical power is generated far from where it is used.

In parallel to the debate about options for ‘supply side’ decarbonisation, another line of thought and debate questions the overall logic of the ‘supply paradigm’ (Lovins 1976; Patterson 1999; Patterson 2007; Bouffard and Kirschen 2008). Alternative approaches, clustered under the generic term ‘demand side management’ (DSM) and ‘decentralised energy’, emerged following the 1970’s ‘oil shock’ and consequent concerns about energy security. For example, the commentator Amory Lovins (Lovins 1976) offered a wide ranging critique of the centralised paradigm in an influential paper ‘Energy Strategy: The Road Not Taken?’. Lovins described the prevailing ‘hard energy path’ as problematic from a number of perspectives: it mistakenly endorses increased energy demand, assuming a causal link with economic growth; it wastes massive quantities of heat; large fossil fuel and nuclear power stations are expensive and represent risky investments that are dependent on scarce resources and uncertain fuel prices; the increased use of nuclear power also poses wider questions about waste management, sabotage and nuclear proliferation. In Lovins’ words the alternative to the ‘hard energy path’ is a ‘soft energy path’: this would comprise local, small scale and flexible electricity generation; the harnessing of ‘waste’ heat; using renewable energy resources such as solar power; and a culture of energy efficiency. Lovins noted prophetically:

‘Perhaps the most awkward (environmental) risk is that late in this century, when it is too late to do much about it, we may find climatic constraints on the coal combustion about to become acute……The soft path, by minimising all fossil fuel combustion, hedges our bets. Its environmental impacts are relatively small, tractable and reversible.’

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3 Oil prices increased sharply due to activities of the OPEC cartel.
Since the mid 1970s, ‘fuel conservation’, ‘energy efficiency’, ‘demand side management’ and more recently ‘distributed generation’, have become part of mainstream political rhetoric in both the US and the UK and are periodically endorsed by government administrations; however in the decades since the ‘oil shock’ there has not been any significant move away from the centralised paradigm, and demand for electricity continues to rise. Moreover, in both the UK and the US market liberalisation has fundamentally changed the relationship between the electricity supply industry, government and the consumer. Where energy planning was once a key government activity, the operation and evolution of electricity systems is now largely dictated by market forces. This poses a challenge for policy makers, who are increasingly decoupled from many of the decision making processes that shape the electrical system.

This thesis explores the prospects for increased demand side involvement in the reduction of carbon emissions, and more specifically those associated with electricity use in the domestic sector. The domestic sector is of interest because, while being responsible for around a third of all electricity demand, households are on the whole only passively involved in reducing emissions. Current approaches to lowering the impact of domestic electricity use typically fall into three main themes namely, how to improve the efficiency of electrical appliances, how to motivate changes in consumer behaviour, and how to generate power locally. The first theme relates to how appliances are designed and the second to what appliances we buy and how we use them. In terms of existing policies targeting consumer participation, the appliance labelling scheme is perhaps the most visible and well established. The labelling scheme is intended to change purchasing decisions by informing consumers and in turn motivate manufacturers to improve the efficiency of appliances. In 2006, following the European Energy Services Directive\(^4\) (ESD) (EU 2006), debate centred on the notion of the ‘smart meter’ as a means of informing the consumer about their energy use, and reduce wasteful behaviour. The meter as a means for demand side management would represent a significant shift in role for what is, at the time of writing, merely a means to electricity retail.

\(^4\) The common name given to the ‘Energy end-use efficiency and energy services’ directive.
Both the labelling scheme and new metering arrangements are thus measures intended to influence electricity use, but it is less clear as to whether they will engender a sustained transformation of domestic ‘energy culture’. For example, how effective is the labelling scheme and is it driving product innovation? What should the new role or roles of the meter be, in view of the climate change agenda? Can metering be developed such that it serves the objective of reducing the environmental impacts of the supply paradigm while also offering a pathway to decentralised alternatives?

These questions concern the present and future of the electricity system, the extent to which we configure the existing system to minimise carbon emissions and, in the longer term, how a sustained transformation of energy culture can be facilitated. The former question requires some understanding of the ‘electrical landscape’ that we aim to adapt. What are the determinants of domestic electrical demand, what are the supply side impacts of this demand, how do these effect carbon emissions, and how can the demand side be adapted to minimise these impacts? The later question pertains to a broader set of issues: what are the technical, institutional and social barriers to system transformation and how might these be overcome?

While the supply paradigm has an extensive retinue of experts and intuitions in its service, the demand side is relatively poorly understood. For example, in technical terms, efforts to measure and model electrical power flows typically focus on large populations, using time resolutions consistent with the operational needs of centralised system operation and electricity retail: this obscures the detail of power flow to individual homes. In terms of policy, ‘market instruments’ have been successfully deployed to support what would otherwise be uneconomic renewable supply side technologies. Conversely the economics of some demand reduction technologies have long been favourable, but take up low, suggesting other more subtle barriers. Given the importance of understanding the wider system that we aim to adapt and rather than examine the merits of specific technologies, or means to change consumer behaviour, this thesis explores the role of measurement and modelling in energy system development.

As suggested by the opening quote attributed to Protagoras, measurement is of fundamental importance; it provides a basis for scientific understanding, which in turn
allows actions to be driven by evidence. While initially this might seem obvious, matters are complicated when considering the detail: what is it that we should measure, how should it be measured, who should collect and receive the measured data, how should data be interpreted, how should data be communicated, what action should be taken?

As our understanding of the world is developed through measurement we can hypothesise as to what intervention may effect change towards our specific objectives. This process requires the development of some form of model, be it mathematical or heuristic, physical or virtual.

For example through the appliance labelling scheme, we have measurements of the energy used by washing machines, and survey data can give us an approximation of ownership and usage. Using these data in a spreadsheet model, we can estimate the national annual electricity demand associated with clothes washing. The labelling scheme is a market intervention since the grading of A – G is intended to influence purchasing decisions. This approach implies a number of assumptions, namely that energy efficiency is a common appliance selection criterion and that the labelling scheme is generally understood. These assumptions could be described as a simple model of the consumer.

Following an intervention we can then return to measurement to identify its effects and to evaluate the accuracy of our modelling system and assumptions. In the case of the labelling scheme this might be an ex-post survey of appliance uptake and usage. Measurement, modelling and management therefore form an interdependent cycle of processes, represented in figure 1, and from here referred to as the 3Ms.
As identified by the brief example of the labelling scheme, management may rely on a number of approaches to modelling, and modelling on a range of measurements and assumptions. The selection of the approaches to the 3Ms used, their repeated application and cumulative experience within an organisation, be it a utility company or government department, could be said to constitute part of their institutional culture. A corollary of this is that the decisions that shape the development a system are naturally framed by the evidence and experience of these practices.

Historical analyses, for example such as that undertaken by Hughes or Unruh (Hughes 1983; Unruh 2000) have stressed the significance of institutional cultures in influencing the development of large technical systems. To what extent and how might the existing and proposed approaches to the 3Ms represent barriers to the development of alternatives to the supply paradigm?

In summary, the 3Ms have potential to impinge on and influence system development in a number of ways and over different time periods: in the present they provide the
evidence and practical means for intervention; in the longer term they frame the perception of the system and influence decision making processes.

1.1 Aims and objectives

The overarching aim of this thesis is to contribute to the policy debate surrounding demand side management and energy efficiency in the domestic sector. It aims to contribute in conceptual terms by:

- Showing how historical, political, social and technical matters have shaped the development of wider electricity system and policy;
- Identifying the shortcomings of existing approaches to the 3Ms in the domestic sector and how these have shaped system development;
- Describing the debate surrounding ‘smart metering’, the likely outcomes and the possible effects on system development;

It also aims to contribute in empirical terms by extending the evidence and available methods for the analysis of demand side interventions by:

- Adding to empirical knowledge about the nature of domestic electrical loads in terms of their temporal and phase dynamics;
- Demonstrating a novel means of modelling the power flow in residential homes and neighbourhoods and allowing comparison of localised interventions;

The thesis is structured as follows: Chapter 2 provides an historic overview of the development of the electrical system, demand side management and energy policy to mitigate climate change. In respect to system development attention is given to identify the complexities in the way that large technical systems ‘evolve’. The chapter sheds light on the difficulties in delivering energy efficiency and how policy has favoured supply-side interventions. Drawing upon academic and government literature this chapter provides a backdrop against which contemporary issues can be discussed.

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5 Large technical systems tend to develop incrementally as opposed to the whole system being planned at the outset.
The following three chapters move on to provide a fuller picture of the wider contemporary electricity system, providing further background about the determinants of carbon emissions. Chapter 3 describes the domestic ‘demand side’ in terms of its contribution to carbon emissions and the associated proliferation of appliances. Appliances\(^6\) represent the final ‘destination’ of power in the electrical system, and their combined usage determines the total residential electricity demand. Despite being familiar everyday objects, what specifically do these appliances represent in terms of energy use and carbon emissions, what policy and technical changes have been implemented, and what are the prospects for the future? Detail is provided on an appliance by appliance basis about their energy use and technological options for efficiency improvements.

Chapter 4 moves on to examine the social and behavioural determinants of energy demand. Given that it is individuals who buy and use the appliances described in the previous chapter, how is the domestic consumer understood in terms energy use behaviour and how can energy saving behavioural change be achieved? The consumer has typically been considered to be a ‘rational consumer’ who, with improved information will reduce energy wastage. But is this an accurate model of the consumer, and how does this model affect policy development? A brief review of the psychological determinants of human behaviour provides a critique of the ‘rational consumer’ model. In the energy policy debate surrounding means to change behaviour, little consideration appears to have been given to methods of persuasion. Building upon the preceding section on behavioural psychology, some ‘rules of thumb’ are identified that increase the chances of persuasion being successful. This provides a backdrop for an examination of the efficacy of the existing labelling scheme and the existing knowledge with respect to energy feedback, the proposed purpose of the ‘smart meter’.

Moving outside the home, chapter 5 considers the generation, transmission and distribution of electricity, asking what are the ‘supply side impacts’ of demand and how can these be mitigated? Because the demand seen by the wider system varies throughout the day, varying amounts of power must be generated and this has impacts

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\(^6\) In this thesis the term appliance is meant to include boilers, water heaters and lighting devices.
in terms of cost and carbon intensity of supply. This chapter describes the mechanisms that are used to manage the variability of demand and explains how these relate to metering. As well as the variable costs of the generation, in addition, the transmission of electricity from the power stations to the home also incurs variable electrical losses: these are briefly explained in terms of their temporal and spatial variability. Finally this chapter return to the domestic meter to explain the function of the meter and how electricity use is accounted for.

Focussing on the meter and its potential importance as a device for measurement and management within the reframed energy system, Chapter 6 describes the political debate surrounding smart metering between 2005 and 2010. With European Directive 2006/32 driving a change in metering arrangements, how was the debate framed and how does this relate to the issues raised in the previous chapters? The debate is discussed in terms of the industrial and political actors involved; their individual narratives and how these may affect the nature of future metering technology. The chapter ends with a critique of the evidence base and the policy making process.

Chapter 7 discusses existing approaches to measurement and modelling of domestic electricity used in academic research; those outside the day to day operation of the electrical system. The shortcomings of existing methodologies are indentified in respect of the renewed interest in demand side management and decentralised energy, with an emphasis on what have become known as ‘bottom up’ or engineering models.

Before the issues raised in the previous chapters are brought together, Chapter 8 briefly examines the culture of energy management in commerce and industry (C&I). There is an established culture of energy management in C&I, and some approaches may be appropriate or adaptable to the domestic sector. This short chapter identifies the crucial role of measurement in energy management in the commercial and industrial sectors, providing background for the discussion chapter.

The first half of the thesis then, as introduced above, provides an overview of the current electricity system, touching upon the technical, social and political aspects of its development, with an emphasis on the domestic demand side.
Chapter 9 brings these threads together and discusses the shortcomings of the current approaches to the 3Ms, as well as the metering arrangements that are likely to emerge in the future. It is argued that the current approaches to the 3Ms have both impinged upon current approaches to demand side management, and have a limiting framing effect upon the perceptions of what is possible.

In light of the findings in the discussion chapter, Chapter 10 revisits the subject of electricity use in domestic appliances. High resolution data, collected through field work are presented which extends the understanding of the power flow characteristics of electrical appliances.

Building on the findings of Chapter 10, Chapter 11 presents a modelling methodology which provides analysts with an additional means of examining demand side interventions. A software framework provides a means to synthesise diurnal\(^7\) load profiles and compare localised interventions at the neighbourhood or household level. The methodology represents a contribution to the field of domestic demand side modelling in providing unprecedented time and phase resolution and a means to manage the associated data complexity. Moreover, given the availability of data, many of the determinants of electricity demand can be examined for sensitivity. The model is then demonstrated with some simple case studies, testing the local effects of reactive power flow, and load shaping scenarios.

### 1.2 Methodology

The research on which this thesis is based is multidisciplinary, involving a range of methods. Chapter 2, covering the history of the electricity system development and policy interventions, is based on an extensive review of academic and grey literature and analysis of government documents. It borrows heavily from Thomas Hughes’ historical analysis ‘Networks of Power’.

\(^7\) 24 hour.
Chapter 3 which describes the appliances on the demand side borrows heavily from the government’s ‘Market Transformation’ grey literature. This is augmented with academic literature regarding the options for improving appliance design.

Chapter 4 exploring the behavioural and social aspects of electrical demand draws from academic literature from the social sciences. Issues relating to psychology largely are drawn from academic text books.

Chapter 5 describes the electricity supply side and the impacts of demand referring to government grey literature, academic papers and internet resources.

Chapter 6, a review of the ‘smart metering’ debate between 2005 and 2010, is based on grey literature, and comments from the contributing constituencies throughout the debate. The author visited the key government and industry events related to metering and documented the key constituents of the debate as they emerged.

Chapter 7 describes current approaches to demand modelling referring to academic literature.

Chapter 8 outlines approaches to demand management in the commercial and industrial based on academic textbooks.

Chapter 9 brings these earlier chapters together in a discussion.

Chapter 10 presents appliance power flow data collected by the author. Data was collected from appliances in the home of friends and relatives using an industrial power analyser. More detail of the methods used is provided in the chapter itself.

In Chapter 11 describes a ‘data driven’ design simulation framework and is largely devoted to the simulation method. The framework is then tested with some small case studies.
2 Background to the debate

2.1 The evolution of electrical systems

2.1.1 The centralised supply paradigm

The long story of electricity generation and its application began in earnest in 1800, when the Italian Alessandro Volta created the first electrical battery. Prior to this invention, electrical experimentation had been limited and often accidental\(^8\). Volta’s electrical cell provided a reliable source of electricity which in turn allowed verifiable experimentation. As the engineering sciences developed throughout the industrial revolution, so the understanding of electricity changed from that of a mysterious force, for example re-animating Shelley’s ‘monster’, to that of an everyday symbol of modernity, such as the light bulb. However, the paradigm shift from science and experimentation to commercial energy services took the best part of a century, with Edison installing his first commercial DC\(^9\) lighting systems in 1882 (Hughes 1983).

2.1.1.1 Large Technical Systems

In a substantial historical analysis ‘Networks of Power’, Thomas Hughes (Hughes 1983) traces the path of electrification from Edison’s earliest developments, to the systems that we are familiar today. Introducing the concept of the Large Technical System (LTS) Hughes broadened the analysis of technical systems, to include social, political, and institutional influences (Hughes 1983). Edison is commonly said to have been able to provide the first effective electrical lighting services because of his refinement of the incandescent light bulb, but Hughes’ wider analysis shows that Edison overcame many obstacles, often unrelated to issues of physics or engineering.

For example, Edison’s entrepreneurial exuberance caused an early example of a ‘high-tech bubble’: with expectations raised beyond the capabilities of deliverable technology, investor worries gave rise to cash flow problems and threatened bankruptcy (ibid). This period of transition, from working prototype to successful

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\(^8\) Readers may recall the story of Galvani, a contemporary of Volta, who accidentally stimulated frog legs with an electrical charge, subsequently claiming to have found ‘natural electricity’. Or perhaps Benjamin Franklin with his key on a kite.

\(^9\) Direct Current is provided by a voltage source that does not oscillate over time.
commercialisation, is now recognised as a challenging phase in the innovation life cycle, sometimes termed ‘the valley of death’\textsuperscript{10} (Foxon 2003).

In the UK, around the same period, government legislation aimed at promoting competition caused a proliferation of system variants which later resulted in the UK falling behind other nations:

‘..the undertakers shall not be to entitled to prescribe any special form of lamp or burner to be used by any company or person…..’

(Section 18 of Electric Lighting Act of 1882 (Hughes 1983))

This provision, which included voltage specification, caused a proliferation of lamp and system operating voltages, making later integration difficult (Butler 2001). With hindsight, encouraging variety in light bulb voltages seems misguided; however this section of the Act was to promote competition by proscribing customer tie ins. The development of LTSs then is influenced by a range of actors, as well as what Hughes calls the ‘system builders’, for example Edison (Hughes 1983).

The decisions of the system builders and governments are however not the only determinants of system development, the LTS itself has been shown to exhibit properties that inhibit change. One such property, which has become known as ‘lock-in’ (Arthur 1989) describes the situation where the incumbent technology and practices present barriers to the adoption of alternatives. Arthur identifies the importance of historic events in shaping the future system and how seemingly insignificant events can lead to very different outcomes. Using theoretical models, Arthur shows how a technology can become dominant when its adoption is self reinforcing, in other words, the more the technology is adopted the more attractive it becomes and in time excludes alternatives\textsuperscript{11} (Arthur 1989).

Lock-in can be a local effect, for example, large organisations tend to invest in refining existing systems, becoming better at what they already do, as opposed to

\textsuperscript{10} In simple terms, a product fails to gain sufficient commercial momentum before initial investment dries up. Moreover, the process of moving from a prototype to ‘product or service in the field’ can give rise to unexpected problems incurring delays and additional costs.

\textsuperscript{11} The reader may remember ‘battle of the formats’ between Betamax and VHS video cassettes.
developing radically different approaches (Unruh 2000). The lock-in of localised institutional practices is exacerbated by wider system inertia caused by what Unruh terms ‘network effects’, comprising:

- Industry and inter-industry coordination such as the creation of standards and design specific relationships.
- The reinforcing effect of private financing mechanisms upon development and diffusion.
- The reinforcing effect of ‘networks of private associations and educational institutions, which develop in response to social and market needs created by the expanding system’ (ibid).

The issue of standards, as mentioned earlier is problematic. Standards are needed to provide interoperability of system components, but explicitly present a barrier to non-compliant technologies. When explicit standards do not exist, institutional norms can also present barriers to new entrants, for example in terms of how a new technology might be integrated into existing practices. Private financing is typically risk averse, focussed on short term returns and less likely to gamble on the markets uncertain response to new technology. The third point is more subtle in that it relates to the effect that a technology has on wider society, which in turn can have a reinforcing effect on the incumbent system. Consider the internal combustion engine (ICE) and road system as an example: academic courses are developed to cater for the needs of the existing system and road user groups campaign to maintain the status quo, with for example fuel taxes. In an analysis of the potential of micro-generation to disrupt the existing centralised paradigm Sauter and Watson summarise this issue of inertia:

‘The institutional embedding process of technology can be understood as the alignment of supporting institutions to the system and a resulting, mutual reinforcing interdependence’

(Sauter and Watson 2006)

Unruh describes the broader system including these interdependencies as the ‘Techno-Institutional Complex’, extending the concept of Hughes’ LTS.
The LTS could then be considered to be beyond the control of any one institution: its development resulting from a confluence of competing technological and institutional influences. Moreover, as the example of prohibiting standards demonstrates, well intentioned interventions can lead to unintended consequences. Hughes refers to the undesired consequences of system development as ‘reverse salients’. A ‘reverse salient’ may also constitute a ‘bottleneck’ which impedes future systems development (Hughes 1983) or when the limited objectives of the ‘system builders’ conflict with wider social objectives, requiring system adaptation.

2.1.1.2 Distribution and AC
Despite the complexities of system development, it was the laws of physics that eventually dictated that Edison’s direct current (DC) systems would be superseded by his competitor’s alternating current (AC) systems. The use of AC allowed voltages to be stepped up and down using transformers, allowing different voltages to appear on different parts of the same system. The key effect this had on the evolution of electrical systems is that high voltages could be used for long distance ‘distribution’ of electricity, now referred to as transmission. The benefit of high voltage is that it allows more power to be delivered through a given electrical conductor. For a given amount of power, a doubling of voltage halves the required current, this in turn reduces the need for expensive conductor materials such as copper and aluminium.

High voltage transmission removed a significant reverse salient in the development of the electrical system: Generators no longer needed to be located near their loads and this allowed economy of scale to be applied to generator plant.

2.1.1.3 Load building
While Edison’s vision had been to replace gas lighting systems, as electrical systems developed, so did the variety of connected loads. This in part was driven by the supplier’s desire to serve a more uniform load throughout the day, as opposed to just lighting in the evenings. This benefited the economics of generators by decreasing the ratio of delivered energy to maximum capacity, otherwise known as ‘load factor’ (Hughes 1983; Patterson 1999). Moreover, running a generator continuously is more
efficient than cycling between on and off states. The importance of load factors remains a fundamental element in power system economics (Smil 2003).

To develop a more favourable load pattern from the ‘demand side’ as well as increased sales of electricity, suppliers embarked on programmes promoting new electrical loads, known as ‘load building’ or ‘load management’ (Patterson 2007). As the notion of load management matured, the electrical motor was seen as key to increasing day time loads when lighting services were in lesser demand (Hughes 1983).

Again using Hughes’ notion of the reverse salient, it is worth mentioning the technical difficulties in the development of AC motors, since these issues were in part solved through the co-evolution of electrical supply technology. DC motors were in widespread use by the time AC was challenging the dominance of DC systems; thus to be a success AC required a viable motor technology. Unlike the incandescent light bulb, DC motors did not operate under AC supply. Early AC configurations used a single phase and it proved difficult to design reliable motors that could be driven by such a supply. However, DC motors had their own shortcomings, primarily their lack of inherent speed control and need of brushes that wear.

Both the shortcomings of DC and single phase AC motors can be overcome by the use of multiphase AC supply with associated motor configurations. The rotating magnetic field that can be produced by multiphase AC is very effective for driving motors and this has influenced the choice of electrical supply system configuration. Moreover, some earlier DC distribution systems had used a three wire configuration to reduce wire losses and these systems offered a platform for rapid conversion to three phase AC supply (Hughes 1983).

The ‘battle of the systems’ between DC and AC took some interesting turns, the pressure of competition spawning technical innovation and different approaches to marketing. Without the benefits of transformers, DC system operators experimented with storage batteries to resolve the issues of using high voltage and supplying peak demand. Batteries were charged at low demand, using high voltage with batteries in series, rewired to parallel and hence lower voltage/high current to serve periods of
high demand. As with the reverse salients of system development, the weapons used by the actors in the ‘battle of the systems’ were not all a matter of engineering and economics. For example, rather than embracing AC, Edison attempted to disrupt the progress of AC systems, using marketing propaganda. To promote the notion of AC being more dangerous than DC Edison supplied a competitor’s generator to a prison resulting in the first state execution using electricity (Hughes 1983).

A more benign example of propaganda can be seen in figure 2, in which load building is promoted through refrigeration with the motto ‘electricity is cheap’.

2.1.1.4 Centralisation
In the first decade of the 20th century, initially in Germany, previously independent systems were interconnected to provide the benefits of economies of scale and
security of supply\textsuperscript{13}. In the US, smaller companies merged into larger companies providing equipment, networks and supply, a process now termed ‘vertical integration’. In the UK, however, earlier developments had created a system ill-equipped for integration:

‘To highlight integration difficulties in the UK, by 1918 in London alone, there were 70 authorities, 50 different types of systems, 10 different frequencies and 24 different voltages.’

(Butler 2001)

It was only after the First World War that the UK electricity systems begin to align with the international trend for wider integration. The Electricity Supply Act of 1926 initiated the creation of the first ‘national grid’ operating at 132,000 volts AC (ibid). By the end of the Second World War, electricity supply was viewed as a social as well as economic objective in the UK, but the war had taken its toll on the system. The Electricity Act of 1947 saw the nationalisation of the UK electricity system, with the Central Electricity Generating Board (CEGB) providing electricity in bulk to Regional Electricity Companies (RECs) (HMG 1947; Butler 2001). The centralised paradigm was entrenched by the CEGB, and manifested in higher transmission voltages, 275,000V and then the 400,000V super grid, as well as nuclear power and larger coal power stations.

While economies of scale and the benefits of load diversity drove up the size of electrical generators, practical issues promoted the building of power stations remote from consumers. Fuel supply and waste removal required appropriate transportation infrastructure, and while river cities like London could use boats to deliver coal to its riverside power stations, many relied on freight trains. A contemporary example of the centralised paradigm is Drax power station situated in Yorkshire, near the coal fields of the north east of England. It requires on average 140 freight train deliveries of 1,400 tonnes of coal a week (Drax 2008). Power stations also tended to be located near rivers, lakes or the sea where the abundant water supply was used to shed ‘waste’

\textsuperscript{13} As a network becomes larger it increases its resilience to failure of individual components, for example a power station.
heat. With electricity being generated remotely from its use, in social terms it became an abstract energy source, disconnected from the fuel it requires and pollution it causes (Patterson 2007).

2.1.1.5 Losses inherent in the centralised system
Most contemporary power stations generate electricity by raising steam to give pressure, and in turn kinetic energy to drive electrical generators (Joyce 2006). Typically steam pressure is converted to kinetic energy through the use of a steam turbine, an evolution of the jet engine: earlier technology had been that of the reciprocating steam engine (Smil 2003). The process of driving a steam turbine relies on a pressure drop across the turbine blades; this in turn represents a drop in temperature of the steam. As the temperature and pressure of the steam decrease through the turbine it becomes progressively less effective for generating power. Eventually heat is expelled through heat exchange to the atmosphere by use of cooling towers or the local water supply.

The thermal efficiency of a modern power station is typically between 30% - 50%, the remaining heat being discarded as described above (ibid). There are some limited examples of power stations’ waste heat being used for industrial processes and residential heating but on the whole it is lost to the environment. Systems that intentionally integrate the provision of heat and electricity are known as Combined Heat and Power (CHP), and these can be nearly twice as efficient as conventional power stations at around 70% (CHPA 2008).14

In a context where C0₂ emissions were not a concern, expelling thermal energy from a power station into the environment represented a logical and practical activity. However when trying to reduce the national aggregate C0₂ emissions it comes to represent a substantial waste of energy, given that, for example around 60% of domestic energy use is ‘low grade’15 to provide space heating. A reverse salient in the

\[\text{14 A broader term cogeneration is used to describe any system that provides heat and another form of energy for example driving mechanical or hydraulic devices.}\]

\[\text{15 Radiator temperatures used for space heating require relatively low temperatures.}\]
present centralised systems is then that waste heat energy from power stations cannot be readily used by third parties because heat is difficult to transport efficiently\textsuperscript{16}.

Another smaller yet significant inefficiency inherent to the centralised paradigm is the presence of electrical losses. ‘Technical losses’ describe electrical losses that are a characteristic of the system, ‘non technical losses’ are energy flows that are unaccounted for, for example, meter fraud, meter errors, non-metered loads, and accounting errors\textsuperscript{17}. Technical losses are caused by impedance in the network for example cables and transformers, and result in energy lost as heat. Losses from any part of the system (excluding some fixed losses in transformers) increase in proportion to the square of the load (Gonen 1986). Technical losses can be reduced by increasing voltage levels or decreasing cable impedance, though these entail costs. Typically a sub-system will be designed to have an ‘economic level of loss’, which is where the marginal value of decreased losses equals the marginal increase in infrastructure costs (Curcic, Strbac et al. 2001).

On the transmission network, because of the diversity of loads, the demand curve is relatively smooth and because the transmission system uses very high voltages, losses are comparatively low (~1.4% of total supply). The opposite is true of distribution networks which lack the load diversity and the high voltages of the transmission system (Willis 1997). Low voltages result in distribution systems being responsible for a larger proportion of system losses (~5.6% of total supply) and this lack of diversity will tend to make the magnitude of loss fluctuate, depending on the coincidence with other loads on the system.

\textsuperscript{16} According to the World Association of Distributed Energy (WADE), transferring heat energy is seven times less efficient than transferring electrical energy, which is in turn seven times less efficient than transferring chemical energy (i.e. transporting fuel).

\textsuperscript{17} For example street lighting is not metered per se, demand profiles are estimated from data relating to the asset base.
2.2 The birth of demand side management

Despite the general trend of increased electricity demand and associated infrastructure development throughout the 20th century, from time to time prevailing economic conditions have given rise to institutional and policy responses aimed at reducing energy demand.

The most dramatic measures are seen when fuel supply is constrained to a point where electricity must be rationed. For example, the strike action of UK miners in January 1972 led to the imposition of the three day week for industry and time based rationing of electricity supply, where domestic supply was cut for up to 9 hours a day (BBC 1972).

The term ‘Demand Side Management’ (DSM) has its roots in the US where, after years of low energy prices and the promotion of consumption (load building), the OPEC oil embargo of 1973 heralded a period of higher energy prices. Energy prices increased the cost of financing, building and operating power plants, and this led regulators and electricity companies to promote alternatives to building system capacity (Gelling 1996). The term DSM was originally coined by Gelling of EPRI in 1984:

‘Demand-side management (DSM) is the planning and implementation of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility’s load shape – i.e. in the time pattern and magnitude of a utility’s load shape. Utility programs falling under the umbrella of demand-side management include load management, new uses, strategic conservation, electrification, customer generation, and adjustments in market share.’

(Gelling 1996)

DSM has since become synonymous with existing utility conservation and load management programmes and lost the broader scope as described above (Chamberlain

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18 While government resisted miners pay claims on grounds of cost, coal prices were held artificially low to further other economic objectives.
and Herman 1996). The earliest DSM programmes introduced ‘Load Management’ where utilities form contracts with customers to reduce their demand at times of peak. This activity does not result in large fuel savings when compared to the ‘rolling’ benefits of energy efficiency, but provides complementary benefits of reduced generator, transmission and distribution capacity requirements. US demand side activity is consistent with a system that experiences significant capacity constraints, so increasing the value of demand side activity (Gelling 1996). Table 1 reflects Load Management’s continuing presence in the US and the growing significance of ‘energy efficiency’ programmes. The promotion of energy efficiency as an alternative to increasing capacity has been advocated since the 1970s, and as Table 1 demonstrates, the idea of energy efficiency has become institutionalised.

<table>
<thead>
<tr>
<th>Item</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Annual Effects – Energy Efficiency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large Utilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual Peak Load Reduction (MW)</td>
<td>13,212</td>
<td>12,873</td>
<td>15,351</td>
</tr>
<tr>
<td>Energy Savings (Thousand MWh)</td>
<td>55,328</td>
<td>52,827</td>
<td>58,891</td>
</tr>
<tr>
<td><strong>Annual Effects – Load Management</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large Utilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual Peak Load Reduction (MW)</td>
<td>16,347</td>
<td>10,027</td>
<td>10,359</td>
</tr>
<tr>
<td>Potential Peak Load Reductions (MW)</td>
<td>33,817</td>
<td>28,496</td>
<td>21,282</td>
</tr>
<tr>
<td>Energy Savings (Thousand MWh)</td>
<td>2,093</td>
<td>875</td>
<td>1,006</td>
</tr>
</tbody>
</table>

By 1990 many US states were enforcing DSM activity, either through capital expenditure targets for efficiency technology or demand reduction targets, in what has become known as ‘input driven’ or ‘output driven’ policy. The regulators stipulated ‘Integrated Resource Planning’ (IRP), where both the demand and supply had to be considered with regard to the provision of energy services. The UK policy discourse had focused on ‘energy conservation’:

‘Only the passage of time will reveal the choices which can be made in the future and energy conservation should therefore become an on-going activity of Government subject to regular review.’

(CPRS 1974)
The term ‘energy conservation’ is not consistent with physics, since energy cannot be conserved per se, rather it can only change form. Commentators have also challenged the usefulness of the now popular phrase ‘energy efficiency’ because it is intangible. ‘Fuel efficiency’ is proposed as an alternative (Patterson 2007), but this is also problematic when considering electricity and the dynamic mix of generators and hence fuels in a centralised system. Whatever the inadequacies of terminology, it is clear that fuel conservation through efficiency was considered a high priority in the UK with the concurrent concerns of coal availability and oil prices (Herring 1999):

‘…Only the government can engender both the sense of urgency and the actual urgency that is needed. In a lecture entitled “Waste, the Threat to the Nation’s Resources” in 1954, Professor Sir Francis Simon said “I do not think it is an exaggeration to say that 30 million tons of coal per year are needlessly sacrificed in heating houses and offices.” Twenty years later the reference to coal is no longer apposite; but the message remains the same.’

(CPRS 1974) (author’s emphasis)

2.2.1 Privatisation and hopes for the demand side

DSM was not universally endorsed however, with some electricity companies claiming it was not their role to engage in energy saving activity (Patterson 1999; Blumstein, Goldman et al. 2005). As oil prices stabilised and remained low through the 1990s concerns about energy security declined, lessening motivations for IRP. In the US interest in DSM subsided and electricity companies resisted the regulators claiming that they should be compensated for the loss of revenue incurred through DSM (Patterson 1999).

In the same period, market principles were being applied to utilities that had previously been considered to be natural monopolies. Chile, under General Pinochet was the first nation to experiment with a privatised electricity market20 (Butler 2001).

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20 The term ‘deregulation’ is sometimes used to describe the privatisation of utilities although it usually requires increased regulation.
In the era of the UK Central Electricity Generating Board (CEGB), despite policies to conserve fuel, electricity supply infrastructure were unquestionably increased to meet demand and power stations were seen as symbols of national pride (Guy 1994). The Thatcher government questioned this logic and in liberalising the electricity market claimed that the system should be driven by customer need21. The Electricity Act of 1989 defined a roadmap for transformation of the electricity market, with a phased transition to retail competition, starting with industrial and commercial consumers (HMG 1989). The first tranche of restructuring saw regional electricity companies (REC) become separate businesses from generating companies. Commentators argued that because the RECs were now the ‘front line of supply’ and a new paradigm was emerging that would enable IRP over the traditional ‘Facilitating Infra-structure Supply’ (Guy 1994). The UK Government also believed that market liberalisation would stimulate the development of improved energy services in the domestic sector (Government 1996).

However, as the UK began to reconsider the possibilities of DSM in the early nineties, IRP was already falling from favour in the US. As states restructured their electricity utilities, a broad collapse was seen in funding for IRP programmes (Chamberlain and Herman 1996; Blumstein, Goldman et al. 2005). This collapse is consistent with the changed priorities of privatised utilities, in that profit-seeking replaced an obligation to serve (Chamberlain and Herman 1996). Moreover, competition in its UK manifestation eventually broke up the regional supply monopolies whose structures aid domestic IRP22. Again, starting in the US, energy efficiency policy discourse shifted from IRP to the notion of ‘Market Transformation’ (MT), in keeping with market liberalisation. The philosophy of MT is distinct from IRP in that it attempts to create a self-sustaining market in energy efficiency:

‘..facilitating the transformation of markets so that they effectively respond to customer needs and public interests in increased energy efficiency’

(Blumstein, Goldman et al. 2005)

(quoting the Wisconsin programme)

21 The Thatcher government’s zeal for privatisation in part stemmed from a perception that workers had exerted too much influence through strike action in the 1970s.

22 With full retail competition consumers switch suppliers thus causing ‘asset stranding’ of energy efficiency measures. The lack of regional monopoly may also reduce the benefits of economies of scale.
‘..funds should be targeted towards programmes that emphasise permanently transforming the market for energy efficient products and services or reducing the barriers, rather than achieving immediate customer specific savings.’

(ibid) (quoting the New York programme)

The notion of MT assumes market failure in that some intervention is deemed necessary to promote energy efficiency. IRP approaches are no longer appropriate because utilities operate in a disaggregated market which imposes barriers, for example the risk of loosing a customer before investments have shown a return.

Following the 2000 and 2001 winter energy market collapses in California, interest in DSM again shifted, back from long-term energy reductions to short-term peak demand reduction to ease system capacity constraints. Connecticut and New York engaged in similar activities to ease transmission system constraints (Blumstein, Goldman et al. 2005). An extreme example of the benefits of ‘load-shedding’ was seen during the California crisis of 2001 where shedding only 300MW would have averted the blackout of the entire region (Hunt 2002).

The notion of energy efficiency persists as a positive aspiration in the energy policy discourse (Smil 2003), and DSM policies continue to evolve in the UK, US and throughout Europe, but as will be explored in the following section, the process of defining, measuring and delivering ‘efficiency’ is problematic.
2.2.2 Delivering and measuring ‘energy conservation’

Energy conservation management is a relatively new discipline, with little scientific and technical literature appearing before 1975 (Jacques, Lesourd et al. 1988). However, well before the oil shocks and subsequent government policy, the fuel efficiency of electricity supply and the electrical efficiency of loads had been steadily improving.

For example the first Watt engine (1776) had an efficiency of 2.5%, by 1860 steam engines could achieve 10%. In 1900 a typical power plant operated at around 5% efficiency, but by 1965 steam turbine plants were achieving around 35% (Jacques, Lesourd et al. 1988). This progress has slowed somewhat and recently built combined cycle gas turbines (CCGT) operate at around 55% thermal efficiency (Smil 2003).

Similarly some demand side technologies have steadily improved through technical innovation, for example street lighting efficiency has increased from 11 to 205 Lumens/Watt since the 1920s (Herring 1999). The efficiency of other lighting services has not improved so markedly, with recent domestic compact fluorescents being around 4 times the efficiency of a modern incandescent bulb. It is worth noting however that the designers of street lighting have the benefit of being able to trade off light quality for efficiency. LPS bulbs emit a very narrow band of light near the red end of the spectrum, and this would be unacceptable for normal use in the home or workplace. This issue makes efficiency difficult to measure as, while for example a light bulb may provide more lumens per watt, its light quality may be different, providing less value in practical terms. In a similar vain Herring sites the example of motor car efficiency which is measured in miles per gallon (mpg) but excludes a valuation of speed (Herring 1999).

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23 These improvements were due to technology substitution (from the filaments to the low pressure sodium (LPS)) in the 1930s, and then subsequent refinements to LPS technology.
In summary, any DSM programme must deliver increased efficiency to that which is already occurring, moreover in the context of climate change policy, improved efficiency must result in reduced carbon emissions.

2.2.2.1 Inter-factor substitution
According to neo-classical economic theory, under perfect market conditions, rising energy prices should cause decision makers to substitute capital and labour for energy. Because ‘energy production and utilisation processes are not immutable’ (DOE 1983) processes can be adapted: it follows that an increase in energy prices should increase the adoption of energy saving processes and technology as substitutes.

The UK government has long recognised the ‘impediments to cost effective energy conservation’, the Department of Energy (DOE 1978) citing:

- Attitudes – giving low priority to energy conservation investments.
- Technological delays – arising from time taken to bring about technological change.
- Economic bias – favouring investment in supply over energy conservation.

The subsequent thirty years have seen a great deal of literature, which have promoted the benefits of energy efficiency, and confirmed sub-optimal inter-factor substitution. A more current list of issues considered to be impeding the diffusion of energy efficiency would include:

- Inadequate private sector incentives for R&D.
- Imperfect information about technological options and their cost implications.
- Transaction costs.
- ‘Principal-agent’ problems. (e.g. the landlord tenant problem24).
- Lack of management incentives (thus low priority).
- Opportunity cost and long payback periods (‘Option to wait’ and energy price volatility).

(Jaffe, Newell et al. 1999)

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24 This is where the property owner does not pay the energy costs of the building and thus does not benefit from efficiency measures.
Energy efficiency and DSM initiatives are intended to overcome these failures by providing information and financial incentives to participants. However as DSM activity developed through the 80s and 90s a growing group of critics argued that DSM programmes were not delivering the benefits claimed by utilities. For example, they cited poor accounting arising from biases in cost-efficiency tests (Braithwait and Caves 1994; Sutherland 1996), ignoring issues of free-riders and additionally (Joskow and Marron 1992), and regressive income distribution effects (Sutherland 1994).

These criticisms on the whole relate to the conflicting responsibilities of the utilities being tasked with saving as well as selling energy. For example, if the DSM policy is ‘input driven’ then there will be a temptation for utilities to choose technology that is most easy to deliver, with less consideration for the value for money or actual energy saved. If the policy is output driven, there will be a temptation to target the lowest cost means: in this case we might see customers with the highest utilities bills offered, for example free insulation, despite their being the most able to pay for it themselves.

2.2.2.2 The rebound effect
While the debate about whether and how to deliver additional energy efficiency is ongoing, another long standing dispute questions the whole rationale of energy efficiency as a means to fuel conservation. Rather than focusing on a ‘cost benefit analysis’ of individual energy efficiency measures, economists have claimed that energy efficiency may actually increase energy use.

There is a primary ‘rebound effect’ or ‘take back’ which is widely accepted by analysts. This is when, for example, a household increases room temperatures, following insulation measures being fitted, because a higher temperature becomes affordable. This kind of rebound has been demonstrated though empirical research and is a well established principle. While it is an issue that needs to be considered in cost benefit analysis, ‘take back’ typically has limits, with energy efficiency measures resulting in net energy reductions (Schwarz, Taylor et al. 1995).

Concern about climate change has re-invigorated debate about the benefits of energy efficiency, especially in its relation to fuel conservation and thus CO₂ emission
reductions. In 1992, the year of the first UN climate change convention, Harry Saunders coined the ‘Khazzoom-Brookes postulate’:

‘With fixed real energy prices, energy efficiency gains will increase energy consumption above where it would be without these gains’

(Saunders 1992)

Saunders brought together the work of Daniel J. Kahzzoom and Leonard Brookes, who both cited the Victorian economist William S. Jevons, who described the effect in his work ‘The coal question’ of 1865:

‘The number of tons of coal used in any branch of industry is the product of the number of separate works, and the average number of tons consumed in each. Now, if the quantity of coal used in a blast-furnace, for instance, be diminished in comparison with the yield, the profits of the trade will increase, new capital will be attracted, the price of pig-iron will fall, but the demand for it increase; and eventually the greater number of furnaces will more than make up for the diminished consumption of each. And if such is not always the result within a single branch, it must be remembered that the progress of any branch of manufacture excites a new activity in most other branches, and leads indirectly, if not directly, to increased inroads upon our seams of coal.’

(Jevons 1865)

In summary, efficiency feeds economic growth and this in turn feeds energy demand. Saunders and others have provided evidence for this effect with macro-economic models. However it is accepted that rebound effects are complex and their magnitude highly dependent on context (Herring 1999; Sorrell 2007). Within the domestic setting, the main concern is ‘take-back’, particularly with heating systems. Estimates of long-run ‘direct rebound’ for central heating lie in the range of 1.4 – 60% (Sorrell 2007).

Other energy services present less of a concern in the sense that refrigerators for example, do not get colder. Customers may choose a larger refrigerator because of its energy efficiency, but choice will more likely relate to the size of family and property, albeit framed by cultural norms. In a situation where a domestic customer saves
money through energy efficiency the secondary rebound effect will depend on what they spend the saved money on.

2.3 Anthropogenic climate change

In October 2007 the United Nations Environment Programme (UNEP) published ‘Global Environment Outlook 4’ (GEO4) a global review of environment issues (UNEP 2007). GEO4 reported on the unsustainable rise of population, resource consumption and environmental pollution. Twenty years earlier GEO4 ’s predecessor, the Brundtland report had already warned of the possible effects of anthropogenic climate change:

‘…increased average global temperatures enough to shift agricultural production areas, raise sea levels to flood coastal cities and disrupt national economies.’

(ibid)

While the level of population versus resources had been of concern decades, when the Brundtland report was published the subject of anthropogenic climate change\textsuperscript{25} was a fringe environmental concern. The intervening twenty years has seen a steady growth of media coverage, academic analysis, public protest and government activity, and climate change now frames both environmental and energy policy debate.

Anthropogenic climate change is caused by human activities that give rise to the release of greenhouse gases (GHGs). The most significant GHGs are carbon dioxide (CO\textsubscript{2}) released from burning fossil fuels, and methane (CH\textsubscript{4}) released with carbon dioxide during the decomposition of organic material. In 2004 carbon dioxide represented 77\% of anthropogenic GHG emissions (IPCC 2007). Figure 3 represents the dramatic rise in annual global carbon emissions since the beginning of the industrial revolution.

\textsuperscript{25} That caused by human activity.
While some of this carbon is absorbed into biological systems, there is a net increase in atmospheric concentrations (Keeling, Whorf et al. 1995). Figure 4 shows the Keeling curve representing annual increases in global atmospheric \( \text{CO}_2 \) concentrations, sampled in Mauna Loa, Hawaii.

Increased \( \text{CO}_2 \) concentration results in earth’s atmosphere absorbing more of the sun’s radiation and thus raising the average temperature of the atmosphere. The current IPCC’s best estimates are that the mean atmospheric temperature will increase by between 1.8 and 4.0 degrees by the end of this century.
Whilst commentators have often correctly stated that the ‘developing’ world will suffer the most from the impact of climate change, at least in the near term, no nation can be fully insulated from risk (UNEP 2007). Predictions relating to global mean temperature rises are varied, but growing evidence suggests that through positive feedback effects, change could be more rapid than predicted, increasing the urgency for action (Hansen, Sato et al. 2007).

In response to the risks posed by climate change world governments have collaborated in the development of the Kyoto protocol, agreed in 1997, binding participants to greenhouse gas emission reductions. The UK is bound to a 60% reduction in CO₂ levels, from a 1990 baseline, by the year 2050. The Kyoto protocol has now been ratified by all major industrial countries except the United States, but negotiation to extend the agreement beyond 2012 have proved problematic.

There are two aspects to anthropogenic climate change which make it an unprecedented problem for humanity. Firstly, ‘developed’ nations have become dependent on fossil fuels and no universal substitute exists. The abundance of coal, oil and gas has resulted in economies where light, heat, motive, and more recently information services are available at relatively low cost and the wider socio-economic system has evolved to use these services in increasing quantities. Secondly, since all nations share the same atmosphere, it is not possible for an individual nation or small group of nations to mitigate the problem alone. The unique nature of the problem is captured by Michalis Lianos:

‘..it is a historical novelty that the organisation of human societies is now subject to another priority than that of the human species or some metaphysical entity’

(Lianos 2006)

The Kyoto protocol represents a positive step, if only for the recognition of collective responsibility. As figure 4 shows however, in the ten years since Kyoto there has been a global increase of atmospheric CO₂ concentrations.
The UK government had claimed to be on course to reach previous target of 20% emission reductions by 2020, but this apparent success was largely due to the ‘dash for gas’ when legislation and economics favoured the development of gas electricity generating plant over coal\(^{26}\). Similarly the former Soviet Eastern European countries now have lower CO\(_2\) emissions, largely due to the collapse of inefficient heavy industry.

Elsewhere, especially in the rapidly growing economies of China and India energy demand is growing rapidly, and technical and social systems are co-evolving in a similar manner to western nations: more cars, more roads, consumerism, and coal electricity generation.

### 2.3.1 Policy responses to climate change

International agreements aside, given the UK’s relative insignificance in a global context, contributing only around 2% to global carbon emissions, it has been questioned whether it is worthwhile for the UK to devote resources to the issues of energy supply and its environmental limits. However the environmental aspects of energy policy have become rapidly institutionalised in both political institutions and commercial enterprises (Lianos 2006). Moreover, in the face of the high risks posed by climate change, governments need to be *seen to act* to maintain their legitimacy (Nohrstedt 1993).

Whilst there is national and international consensus regarding the need for action to combat climate change, the specifics of the policy debate are framed by national interests and prevailing political ideology. In turn private sector responses are framed by incumbent organisational cultures, competition and the need for profit. Since liberalisation, UK energy policy has been strongly influenced by the ideology of market forces, albeit regulated to ensure effective competition. This has influenced the discourse to a point where the notion of ‘energy planning’ (read IRP) has become ‘almost unmentionable’ (McVeigh and Mordue 1999).

However, the UK has undergone a transition from a period of energy self sufficiency, to become a net importer of fossil fuels: gas is our largest source of primary energy and around 80% is now imported (POST 2004). Whilst promoting energy market liberalisation, the UK is exposed to the volatility of world markets, with the majority of other participants being regulated or government owned monopolies, for example Russia’s Gasprom. The UK suppliers have blamed the lack of European market liberalisation as the cause of gas price increases in 2006 (BBC 2006), but it is unclear how far market liberalisation will progress in an atmosphere of increasing concern about security of supply and climate change. Thus despite the prevailing UK ideology of ‘no energy planning’ concerns about supply and reserves of fuel are once again at the forefront of government concerns. Whilst it is beyond the scope of this thesis to explore this issue any further, all policy considerations relating to climate change are necessarily framed by considerations of the energy security. In practice however these themes are often complementary. Load management has the potential to reduce electricity use and ‘keep the lights on’ in times of system stress; energy efficiency can reduce emissions as well as fuel usage.

Assuming the need for policy to effect CO₂ emission reductions, re-assessing the current electrical system in terms of current policy objectives reveals clear reverse salients:

- The majority of generators depend on fossil fuel, causing CO₂ emissions.
- The majority of fossil fuel energy is discarded as heat.
- Around 10% of electrical energy is lost in transmission and distribution.

These issues present a challenge for policy makers in that they are fundamental characteristics of the existing system and there are significant barriers to overcome, namely:

- Limited alternatives to fossil fuel energy supply.
- Weak economic drivers for alternatives.
- Lack of facilitating infra-structure for alternatives.
Addressing these barriers has become the focus of much of the policy response to climate change, with an emphasis on the decarbonisation of electricity supply. The development of energy policy has historically been a national concern and some of the landmark acts of parliament have already been mentioned, however the trans-boundary nature of climate change has led to an increased role for the European Union in shaping energy policy. The UK’s energy policy portfolio comprises European wide policy (Statutory Instruments), for example the Emission Trading Scheme (ETS), and domestic policy, some of which developed to comply with European Directives. The European Emission Trading Scheme (ETS) provides a system of carbon rationing and trading among larger fossil fuel consumers: this is intended to minimise the carbon output from existing generator plant, through carbon efficient despatch, and encourage investment in low carbon and energy efficient technology. In the UK the Renewable Obligation Commitment (ROC) defines market-wide targets for renewable electricity generation, again with trading of credits intended to increase market efficiency.

These measures affect the carbon intensity of all electricity demand and these ‘supply-centric’ mechanisms have tended to be favoured against options for demand-side participation (Bilton, Ramsay et al. 2008). This bias may be in part due to the lack of empirical evidence, with historic trends showing increased efficiency concurrent with increased demand, and notions of rebound as introduced earlier in this chapter. Lovins identifies another possible bias towards the incumbent paradigm:

‘Any demanding high technology tends to develop influential and dedicated constituencies of those who link its commercial success with both public welfare and their own. Such sincerely held beliefs, peer pressures and the harsh demands that work itself places on time and energy all tend to discourage such people from acquiring a similar thorough knowledge of alternative technologies and the need to discuss them’

(Lovins 1976)

Moreover the cumulative experience of the perceived failures and criticism levelled at DSM, as discussed earlier, will also have a negative framing effect. However, it is on the whole, not the technology measures that have been criticised in DSM but the
effects of policy and the actions of the utilities. Whilst this is perhaps an obvious point, attribution errors occur often, particularly when failure evokes an emotional response. In other words we must be wary of ‘throwing the baby out with the bath water’ because of previous experience.

It is also worth noting that the demand side has a richer complexity than the supply side, with many more autonomous loads compared to a relatively small number of generators on the ‘supply side’ (Smil 2003). This complexity necessitates a range of measures and a piecemeal approach to change on the ‘demands side’, compared to the quantifiable ‘single fix’ of, for example, a nuclear power plant. The complexity has practical implication in terms of delivery, but is also likely to affect the ability of individuals to conceptualise the more complex alternative demand side scenarios. It is perhaps then not surprising then that government, whilst advocating efficiency and decentralised power, has tended to favour larger centralised supply-based solutions.

Despite the above, concern about the environmental effects of climate change has swelled the ranks of those advocating energy efficiency and DSM. Environmental groups now lobby for an energy policy that promotes demand side solutions to the climate change problem, while typically maintaining an anti-nuclear position. See for example Greenpeace’s ‘Energy Revolution: a sustainable pathway to a clean energy future for Europe’ (Teske 2005), or ‘Nuclear power, climate change and the Energy Review’ from Friends of the Earth (FOE 2006).

With the utility companies no longer under government control, UK energy policy development often involves lengthy and complex negotiations between the government, regulator and the private sector actors. The opinions of other ‘stakeholders’, for example environmental groups and academics, are typically gathered in consultations prior to policy development; proposals are then developed and in complex cases this process is iterated. The utility companies are in a strong position in these negotiations: firstly, the majority of data pertaining to the systems operation is now in private hands; secondly the experts who were previously serving government objectives are now in the employment of the utilities. The world view of the utility company is then likely to have a powerful effect upon the development of energy policy. For reasons of self interest however the utilities need to maintain
legitimacy in respect to the climate change agenda and hence avoid punitive government actions.

Despite the biases and inertia that have been discussed, there are a range of current UK policies that should result in some reconfiguration of the ‘demand side’:

- Climate Change Levy (CLL), an energy tax for commercial and industrial consumers who do not fall within the ETS (HMR&C 2001).
- The Carbon Reduction Commitment (CRC), a mandatory demand side emission trading scheme for large business and public sector organisations (from 2010) (Defra 2007).
- The Carbon Emission Reduction Order (CERT), this supersedes the Energy Efficiency Commitment (EEC) and obliges suppliers to deliver carbon emission reductions as opposed to ‘energy efficiency’ (HMG 2008).
- Energy efficiency labelling, a Europe wide scheme intended to promote energy efficiency technologies through mandatory labelling (EST 2008).
- Energy efficiency minimum standards, prohibition of appliances with the lowest efficiency (EU 2005).
- National targets and rebate schemes for the adoption of micro-generation (HMG 2004; HMG 2006).
- Building standards (BRE 2009).
- Public information campaigns (Bilton 2005).
- Support for micro-generation (DTI 2006).

These policies do not all fall under Gelling’s definition of DSM programmes, since apart from CERT, they are not delivered by the utilities; this is consistent with market liberalisation in that the utilities are now profit-seekers as opposed to serving social objectives. Some of these measures are however clearly rooted in the era of IRP; the EEC/CERT policy is in essence a simple form of IRP. Of the measures listed, perhaps only the CRC can be considered a novel approach, distinct from the methods of historic IRP programmes, but its effectiveness is yet to be proven. Importantly however since this approach makes emission reductions a director/board level responsibility, it will to some extent, directly affect organisational culture.
The UK policy portfolio in 2010 then is a paradoxical mix of traditional IRP in parallel with a post liberalisation approach of ‘market transformation’ represented by the appliance labelling scheme.

The CERT scheme is in essence similar to the previous EEC scheme, with a significant difference in that its targets have changed from final energy use targets 130TWh (2005-2008) to CO₂ emission targets. CERT which runs from 2008 – 2011 commits the suppliers to deliver ‘154 million lifetime tonnes of carbon dioxide’ (OPSI 2008). Credits towards these targets are awarded based on ex-ante calculations of the expected lifetime carbon reductions of an intervention. In the case of electrical appliances this is the expected benefit from the substitution of an old model for a more efficient equivalent. The mechanism also includes credit ‘uplift’ for technology that is deemed worthy of additional promotion, for example ground source heat pumps and external building insulation (ibid). This uplift results in the possibility of the targets being met but with less actual emissions reduction, this is deemed appropriate given the potentially long term benefits in specific areas of ‘market transformation’ (Eyre 2003). The CERT mechanism is also skewed towards another government objective of eliminating ‘fuel poverty’ and accordingly 40% of efforts must target the ‘fuel poor’.

The earlier criticism of utility driven DSM have resurfaced in the contemporary debate, particularly in respect to CERT. For example, one measure adopted by the utilities to meet targets was the unsolicited delivery of energy efficient light bulbs. This practice has resulted in around 180 million compact fluorescent bulbs being delivered, but there was concern that not all of these bulbs were being used, and the practice was banned from January 2010 (Which 2010). Before the ban came into force some utilities were then criticised for continuing the practice with mass mail-outs in the intervening months in order to meet their obligations (Which 2010). Similarly, accusations of double counting were levelled at suppliers in respect to the delivery of loft insulation. Suppliers had subsidised both the sale of loft insulation for DIY activity as well as professional installations. Double counting was occurring because

27 The term ‘fuel poor’ is used as a description for households who’s utility bills represent 10% or more of their income.
many of the professional installers were using the subsidised product intended only for DIY use (Webb 2010). These two problematic activities, which represented a significant proportion of supplier’s CERT targets, highlight the problems of *ex-ante* calculation, accounting errors and ‘additionality’. Perhaps more importantly they also shed light on the gulf between the spirit of the legislation and the practices of the ‘big six’ energy suppliers.

It is of interest to note that the wider policy portfolio tends to focus on larger organisations using regulation, tax or market instruments. Responsibilities placed upon small organisations and individuals have been conspicuously absent from UK policy. This tendency sees the costs of CO₂ emission abatement passed on to customers through utility bills as opposed to direct taxation. The domestic customer is largely disengaged from the activities of emission abatement, other than through personal choice.

This said, since the miner’s action of 1972 the UK government has from time to time conducted media campaigns aimed at reducing wasteful behaviour. These have not attempted to challenge lifestyles fundamentally, but have instead focussed on the benefits of, for example, not leaving office computers on overnight, or not overfilling your kettle (Bilton 2005). The notion of domestic ‘energy wastage’ as a problem persists, at least on the fringes of the policy debate and has re-emerged as one of the justifications for the introduction of ‘smart meter’ technology: the principle being that if people could ‘see’ what energy they are using they would waste less, although there are low expectations as to deliverable benefits (Ofgem 2006).

European policy however, as defined through the ESD clearly aspires to a wider transformation of the demand side, and promotes the notion of ‘energy services’ as opposed to simply energy supply: Improved metering is seen as a key ‘enabler’ for such a transition. The ESD goal of greater public participation is consistent with the guidance of other organisations. For example, the United Nations Environmental Programmes (UNEP) sustainability guidelines promote the right of the individual to participate in energy services and environmental conservation (Hake and Eich 2006). Similarly, the Aarhus convention recently adopted by the EU, enshrines the principle
of the right to information with regards to environmental impacts and the means to act (MacDonald and Makuch 2006).

Demand side participation is then once again at the centre of the energy policy debate and is being advocated by the powerful European Council, not only environmental mavericks. This said it is unclear whether this high level endorsement and associated legislation will radically transform energy culture. The biases and inertia already discussed albeit in abstract terms may continue to hold back the development of alternatives to the supply paradigm in a period where climate change mitigation needs all the innovation that can be mustered. The following chapters aim to identify specific aspects of the existing paradigm that may be impinging upon demand side developments, with a focus on approaches to measurement, modelling and management. To reiterate the introduction, measurement and modelling provide the means for management, but what are the practical limitations of the existing approaches? We have also discussed how practices become embedded in institutional cultures. The embedded approaches to the 3Ms, which were developed to serve the needs of the existing system, may themselves be limiting the perceptions of both what is desirable and achievable. These perceptions may influence the formation of policy, resulting in poor outcomes, in turn the poor outcomes may re-enforce negative perceptions and further embed the status quo.
3 The ‘Demand Side’: Behind the meter

3.1 Introduction

In 2007 combustion of fossil fuel resulted in emissions of ~544 Mt CO$_2$ contributing 85% of the UK’s ‘basket of green house gases’ or ~636 Mt CO$_2$ equivalent (CO$_2$e). (Defra 2009). Total electricity demand was ~400 TWh, which represented 225 Mt CO$_2$e, or ~35% of total emissions. In the same year the domestic sector accounted for 34%, ~115 TWh, of final electricity consumption, close to the industrial sector at ~118TWh. Given these figures we can see that electricity use in the domestic sector is responsible for ~12% (35% x 34%), or ~76Mt of total UK CO$_2$ emissions (BERR 2009). This figure includes a component of power plant and pumped storage facility demand, typically around ~6% and losses of ~7% of total demand. Losses comprise technical losses in transmission (~1.4%) and distribution (~5.6%), with a small remainder being non technical losses, fraud and unmanaged loads (DTI 2006). Figure 5 shows a ten year trend in final demand by sector including the electricity supply side and losses.

Figure 5 Annual electricity demand trends by sector (BIS 2009).
3.2 The relative significance of electricity use in the home

Efforts to improve the energy efficiency of the residential sector have been and continue to be, focussed on the provision of insulation measures, namely cavity wall insulation, loft and hot water lagging to reduce space and water heating losses. For an example see the ‘Domestic energy efficiency primer’ from the Energy Saving Trust (EST 2006). This focus is consistent with heating demand being the single biggest end use of energy in the UK domestic sector; figure 6 represents the relative proportion of energy ‘seen at the meter’ for four categories of energy use. Note that the government department business enterprise and regulatory reform (BERR) uses the metric million tonnes of oil equivalent (mtoe).

The majority (85%) of centrally heated homes currently use gas boilers (BERR 2008), and newly fitted boilers must be high efficiency condenser types, at around 86% efficient (EST 2009). Older gas boilers can be less than 70% percent efficient and consequently boiler replacement is both promoted by organisations such as the EST and subsidised by energy suppliers as part of CERT. Alternatives to gas central heating are often more carbon intensive, for example where no gas supply is available, electrical storage heaters, or oil powered boilers are used as an alternative. Although not yet widely adopted in the UK domestic sector, heat pump technology offers another possible approach to space and water heating. Using the same principle as a refrigerator, but in reverse, thermal energy is extracted from the environment, air, soil, water or bedrock and fed into the home. Like a refrigerator, this process takes electrical energy, and the ratio of energy out to energy used is termed the Coefficient of Performance (CoP) and currently this results in net carbon emissions similar to a gas boiler (EST 2009).

Given the above, in homes already fitted with efficient boilers, building insulation (including draft proofing) currently represents the only measure that can significantly reduce space heating\textsuperscript{28} related emissions, and this will continue to be the case unless the electrical supply side is dramatically decarbonised. In a scenario where gas and

\textsuperscript{28} Here we exclude the possibility of lower temperature expectations of thermal comfort. The average internal temperature of UK homes has steadily increased over recent decades from 12.7 C in 1972, to 18.0 C in 2004. Increases have occurred in both centrally and non-centrally heated homes.
electricity have similar costs per kWh, a rational consumer seeking to reduce their energy costs might consider if they had appropriate levels of insulation and whether their boiler was suitably efficient.

![Figure 6 Domestic energy demand by end use, data source (BERR 2008).](image)

The above logic does not hold true however if our objective is to focus on reducing carbon emissions. Firstly the kWh seen at our electricity meter excludes the energy used in generating and delivering the electricity to the home. If we are to represent carbon emissions accurately then we must also consider the fuel mix of our electricity generator portfolio and the relative emissions per primary fuel.

Figure 7 represents an approximation of the carbon intensity for the four energy service categories, derived from the same data as figure 6, but weighted to the average carbon intensities of electricity production. From this, we can see that non-space heating energy services contribute the majority of carbon emissions attributable to the domestic sector, and importantly the category of lights and appliances is the highest source of carbon emissions after space heating. Moreover, figure 7 may underestimate the relative costs of non-space heating services since cooking and lighting contribute to electricity demand peaks and thus incur higher supply cost and losses than the average.
The dip seen in the non-space trend is a result of the development of gas generation after market liberalisation.

![Figure 7 Domestic energy demand by carbon emissions, derived from (BERR 2008)](image)

The two previous graphs demonstrate the importance of making clear distinctions between metrics:

- Figure 6 shows us that energy demand for all domestic services, except cooking, are steadily increasing and space heating is the largest use of the energy used in homes.
- Figure 7 gives us a macro-view demonstrating the efficiency problems associated with centralised electricity generation and the effect of electricity generation mix on carbon intensity.

The data used in figure 7 included losses and generator plant energy demand (Knight 2008) and so represent all domestic energy related carbon emissions. However, temporal variations in carbon intensity and losses are not accounted for. Given that, in terms of carbon emissions, non space-heating applications are as significant as space-heating, what do these applications comprise and how might they be mitigated?
3.2.1 The proliferation of electrical appliances

In the year 1900 the provision of domestic energy services was very different from those seen today. Town gas was the dominant fuel in providing light, and this remained the case until the 1920s, with electrical lighting reaching parity with gas, in Lumen Hours produced, in around 1930 (Fouquet and Pearson 2006).

However, even before electricity dominated lighting services, the early decades of the 20th century gave rise to many inventions that have become familiar everyday appliances:

- The first commercially available vacuum cleaner from the Hoover company in 1908 (Hoover 2009).
- The development of electric ovens, with thermostatic control in the 1930s. (Science_Museum 2003).
- The first electrically driven washing machine was invented in 1908 (Fisher 1910), but became widespread after the Second World War (Science_Museum 2003).
- Widespread adoption of refrigerators following the General Electric all steel refrigerator in 1927 (Science_Museum 2003).
- The radio, with public UK broadcasts starting in 1922 (Bowden and Offer 1994).

These appliances represented the ‘state of the art’ at the time and initially were the preserve of the rich. For example the refrigerator in figure 8 cost $525 in the US 1927, and this was half the price of its competitors (Science_Museum 2003).
The proliferation of appliance types, their falling cost, falling energy prices and the load building activities of energy suppliers have resulted in a growth of electricity demand throughout the 20th century.

The evolution of washing machine technology demonstrates an incremental substitution of motive energy and thermal energy, figure 9 shows four examples in this evolution. Image 1 represents the state of the art in Victorian manual washing machines with an integrated mangle (used for partial drying). The electric motor in image 2 is used to agitate the wash by rotating a drum, as well as driving the mangle mechanism. While electrical spin drying machines were available as separate machines, the mangle persisted in appliance designs, as can be seen in image 3. It was only in the early nineteen sixties (image 4) that machines were developed to perform the complete wash cycle including a spin dryer.
Figure 10 represents an estimate of the increase in electrical services by appliance class and their corresponding contribution to overall national demand, excluding
space and water heating. The spread of demand amongst different appliance types suggests that there is no clear target for electrical end use efficiency in the domestic sector, with each service type requiring analysis of prospective options.

Two appliance categories, lighting and cold, show a recent small decline in consumption, this is due to improvements in efficiency caused, on the whole by the EU energy efficiency labelling scheme and minimum efficiency standards, discussed in the following chapter.

The varieties of, and ownership of, consumer electronics and ICT continues to increase and combined are now the biggest source of appliance demand in the home. This is not because they intrinsically use a lot of power, but because they are often left on, or in standby mode (MTP 2008).

The rapid growth trajectories of these two categories is consistent with findings of Bowden and Offer, who identified that the adoption of consumer electronics reaches saturation much more rapidly than appliances such as the washing machine (Bowden and Offer 1994).

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![Figure 10 End use energy demand per appliance class (BERR 2008).](image)

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29 The term wet refers to washing machines, tumble dryers and dishwashers, cold to refrigeration, consumer electronics to televisions and Hi-fi etc, and ICT to computers and communication related devices.
30 Discussed in more detail in the following chapter.
Previous Market Transformation Programme (MTP) data had referred to consumer electronics as ‘brown goods’, this change in name reflects the growth in the variety of electronic goods, and the increase in computer related demand has led to the need for a distinct Information and Communication Technology (ICT) category.

Table 2 lists government aspirations for ‘market transformation’ in each category, with a clear emphasis on demand reductions in lighting and electronic goods.

Table 2 MTP Reference and projected scenarios for final domestic electricity demand (GWh)
(MTP 2008)

<table>
<thead>
<tr>
<th></th>
<th>REF 2007</th>
<th>% of total</th>
<th>REF 2020</th>
<th>% of total</th>
<th>P1 2020</th>
<th>% of total</th>
<th>Savings</th>
<th>% saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>15,578</td>
<td>17.2%</td>
<td>13,706</td>
<td>12.4%</td>
<td>10,962</td>
<td>14.3%</td>
<td>2,744</td>
<td>20.0%</td>
</tr>
<tr>
<td>Wet</td>
<td>14,374</td>
<td>15.8%</td>
<td>15,501</td>
<td>14.1%</td>
<td>14,701</td>
<td>19.2%</td>
<td>800</td>
<td>5.2%</td>
</tr>
<tr>
<td>Lighting</td>
<td>17,216</td>
<td>19.0%</td>
<td>19,185</td>
<td>17.4%</td>
<td>8,923</td>
<td>11.6%</td>
<td>10,262</td>
<td>53.5%</td>
</tr>
<tr>
<td>Consumer</td>
<td>18,489</td>
<td>20.4%</td>
<td>34,024</td>
<td>30.9%</td>
<td>22,722</td>
<td>29.6%</td>
<td>11,302</td>
<td>33.2%</td>
</tr>
<tr>
<td>ICT</td>
<td>11,969</td>
<td>13.2%</td>
<td>14,617</td>
<td>13.3%</td>
<td>7,139</td>
<td>9.3%</td>
<td>7,478</td>
<td>51.2%</td>
</tr>
<tr>
<td>Cooking</td>
<td>13,171</td>
<td>14.5%</td>
<td>13,102</td>
<td>11.9%</td>
<td>12,301</td>
<td>16.0%</td>
<td>801</td>
<td>6.1%</td>
</tr>
<tr>
<td>Total</td>
<td>90,797</td>
<td></td>
<td>110,135</td>
<td></td>
<td>76,748</td>
<td></td>
<td>33,387</td>
<td></td>
</tr>
</tbody>
</table>

The following section now examines the ownership levels, details of energy use, and the scope for intervention within the specific appliance categories.
3.2.2 Lighting

In 2008 the majority of UK domestic lighting equipment was fitted with incandescent bulbs, not dissimilar to those used at the birth of domestic electricity supply. While no up to date data was publicly available at the time of writing, projections have been made by the MTP, based on research data from 1996, these are summarised below.

**Table 3 Estimated distribution of fitted lamp types (MTP 2008).**

<table>
<thead>
<tr>
<th>Technology</th>
<th>% of fittings 1996</th>
<th>% of fittings 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFL</td>
<td>N/A</td>
<td>27.8%</td>
</tr>
<tr>
<td>Linear Fluorescent</td>
<td>7.4%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Halogen</td>
<td>0.6%</td>
<td>6.2%</td>
</tr>
<tr>
<td>GLS 40W</td>
<td>21%</td>
<td>15.1%</td>
</tr>
<tr>
<td>GLS 60W</td>
<td>48%</td>
<td>34.8%</td>
</tr>
<tr>
<td>GLS 100W</td>
<td>N/A</td>
<td>15.5%</td>
</tr>
</tbody>
</table>

At present the compact fluorescent light (CFL) is the only widespread alternative to the incandescent light bulb. The CFL is around three to four times as efficient, and has a lifetime of 5 – 10 times of that of an incandescent lamp (MTP 2008).

The continued prevalence of the incandescent lamp has led government to adopt a position of intervention, with policy aiming to increase substitution to more efficient technology. The UK Market Transformation programme (MTP) focuses on the opportunities for increased use of fluorescent lighting and consider that Light Emitting Diodes (LEDs) offer the best prospect of higher efficiency lighting in the future. Other technologies are considered to have only limited benefits, for examples improvements on incandescent technology, and others are pre-commercial, for example organic LEDs (MTP 2008).

Attempts have been made to improve consumer awareness of the benefits of CFLs, including the European labelling directive and public awareness campaigns (Bilton 2005). It is unclear how effective these have been since no recent publicly available data exists for uptake, but the aggregated energy consumption data presented earlier suggests we have not yet seen any fundamental change in domestic lighting services.

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31 General Lighting Standard (typical incandescent bulb)
32 2010
This failure is indicative of the challenge in driving voluntary change in even the simplest of services.

The lighting ‘efficiency gap’ is in part due to attitudes towards CFLs; negative perceptions persist about light quality, flicker and warm-up time, despite these issues having been largely addressed (Canseco 2008). In response to the lack of technology substitution, regulations have been developed mandating CFL only fixtures in new building developments (DCLG 2006), and a voluntary agreement to incrementally phase out bulbs over a certain wattage was agreed by government and major retailers (Taylor 2007). However the voluntary agreement has been superseded by a phased European ban of incandescent bulbs (EST 2010).

The MTP had claimed the P1 scenario was ‘achievable through normal market mechanisms (including expected changes in the market for different types of lamps) and the supporting policies outlined in the Energy White Paper in May 2007.’

The MTP P1 scenario requires that the average sales of domestic lighting products would have to achieve efficiencies indicated below (MTP 2008).

<table>
<thead>
<tr>
<th>Year</th>
<th>Efficiency lumens/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>35.6</td>
</tr>
<tr>
<td>2015</td>
<td>28.9</td>
</tr>
<tr>
<td>2020</td>
<td>35.7</td>
</tr>
</tbody>
</table>

This is compared to a 2007 average of 17.7 lumens/W, representing a dramatic shift in buying habits, thus the move to regulatory approaches appears justified. The dip then later rise is an artefact of the elimination of incumbent incandescent population and the rise due to incumbent CFLs needing less frequent replacement.
3.2.3 Cooking

The Defra/MTP cooking category includes all appliances used for cooking and preparing hot drinks, namely; hobs, ovens, microwaves, kettles, toasters but does not include kitchen ‘gadgets’. Table 5 shows the ownership statistics of a broader set of kitchen equipment as estimated by the Energy Saving Trust.

<table>
<thead>
<tr>
<th>Penetration of domestic cooking appliances</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooker hoods</td>
<td>18%</td>
</tr>
<tr>
<td>Deep fat fryer</td>
<td>34%</td>
</tr>
<tr>
<td>Electric hob</td>
<td>46%</td>
</tr>
<tr>
<td>Electric oven</td>
<td>59%</td>
</tr>
<tr>
<td>Kettle</td>
<td>97%</td>
</tr>
<tr>
<td>Microwave</td>
<td>83%</td>
</tr>
<tr>
<td>Sandwich toaster</td>
<td>33%</td>
</tr>
<tr>
<td>Slow cookers</td>
<td>20%</td>
</tr>
<tr>
<td>Toasters</td>
<td>80%</td>
</tr>
</tbody>
</table>

3.2.3.1 Ovens
The MTP estimate the average consumption per use of new ovens to be around 1.09kWh per use, compared to 1.2 kWh before the energy labelling was introduced. The average annual energy consumption of a new oven has fallen from 224.5 kWh in 2003 to 208.4 kWh in 2007 through a combination of higher sales of more efficient ovens and reduced usage. The MTP also estimate that around 60% of new ovens have a standby power using 5W (Defra 2008).

There are large cultural differences in the way different nationalities use their ovens, largely related to the favourite national dishes (Kasanen 1997) so while appliances may be very similar, aggregate demand varies considerably from country to country. Detailed empirical evidence on cooking appliance usage in the UK is scarce. Mansouri et al. provide results from a survey (n=586) of the weekly usage of domestic ovens, seen in figure 11 (Mansouri, Newborough et al. 1996).
Because heating elements in ovens represent a simple resistive load, we can use appliance specifications to ascertain the power rating of the heating elements rather than having to measure many devices. Oven elements are typically rated between 1 and 3 kW\(^3\).

### 3.2.3.2 Hobs

Gas hobs are traditionally the most popular type in the UK, found in 56% of homes (MTP 2008). Electrical hobs adopt a range of approaches, the most common being the ‘cooker ring’ and infra-red hob which conduct heat to the pan. Both gas and electric hobs are around 40% efficient in terms of the energy conducted into the pan.

The induction hob is a more recent approach; it induces current which heats the pan itself (the pan must be made of metal). Induction hobs are estimated to be approximately 30% more efficient than traditional designs (ibid) and represent around 5% of sales.

Conventional hobs are estimated by the MTP to consume 0.72 kWh per use (Defra 2008). More detailed data on hob usage, as well as other cooking habits is scarce. In a rare example of detailed analysis with large sample groups, Mansouri et al. identify some clear patterns in hob usage. Figure 12 shows hob activities categorised by ring and duration of usage. Ring 1 (highest power) used for 15-30 minutes is the most

---

\(^3\) See the appendix for detail.
common activity. Other rings tend to be used for less time and rings 3 and 4 are often not used at all.

![Figure 12 Hob usage statistics (Mansouri, Newborough et al. 1996).](image)

### 3.2.3.3 Microwave ovens
The MTP estimate energy consumption per use to be ‘0.945 kWh based on actual measurements of 1.39 kWh for full power function and 0.5 kWh for defrosting.’. Usage is estimated to be an average of 96 times per year (MTP 2008). Average standby consumption is estimated to be 3.6 W, accounting for 0.4 TWh for the total stock of microwave ovens in 2007 (Defra 2008). This is higher than reported by Ross and Meirer who give report an average 2.8W in a range of 1.6 – 3.9W (Ross and Meier 2000) and this is consistent with an increase in microwaves with electronic controls.

### 3.2.3.4 Kettles
The energy use of kettles is clearly related to the level to which they are filled. The MTP scenario uses an assumption that kettles on average boil 1 litre of water per use (MTP 2008). No evidence was found regarding actual kettle filling habits. At an estimated 90% efficiency each use of a kettle is calculated to be 0.11 kWh, and the number of uses per year is estimated to be 1,542 (MTP 2008).
3.2.3.5 Summary

Whilst cooking represents one of the lower energy demand categories of the MTP end-use categories, it often involves high levels of power and is often coincidental with peak demand\textsuperscript{34}. The method of cooking and choice of technology used can have a significant effect on the amount of energy used in preparing meals (Wood and Newborough 2003). For example cooking fresh vegetables to similar effect can be achieved through being:

- Boiled with excess water in pan
- Boiled with appropriate amount of water
- Boiled without pan lid
- Boiled with pan lid (Brundrett and Poultney 2007)
- Steamed
- Pressure cooked
- Slow steamed using the ‘conservative method’\textsuperscript{35}
- Microwaved

This list attempts to reflect an estimated ‘reverse merit order’ with boiling without a lid, with excess water, being the least efficient method. Testing these options is beyond the scope of this thesis, but research has been conducted for the MTP which analysed the benefit of substituting conventional electrical heating with a microwave (MTP 2008). This analysis showed that using a microwave for all or part of the cooking process could reduce energy consumption in a wide range of activities by between 21 to 81%. However the research also revealed that microwaves are currently only used for around 20% of all cooking processes.

The report also includes micro data about the duration and energy consumption of a number of cooking activities and this has been used in defining parameters for the modelling process described in chapter 11.

\textsuperscript{34} The consequences of this will be discussed in more detail later.
\textsuperscript{35} This is a traditional low energy technique involving a small amount of water in a pan kept just below boiling, with a lid, in effect steaming the vegetables.
Given the efficiency penalties of centralised electricity production, cooking with gas, where available, represents a significantly lower carbon alternative to electricity. However electricity to gas substitution is not, in 2010, promoted by the government funded Energy Saving Trust:

“Electric ovens with fan assist are the most efficient”

(Personal communication with Jane\textsuperscript{36} at EST)

3.2.4 Cold

The cold category refers to appliances that provide refrigeration services, namely stand alone refrigerators and freezers, and combined fridge-freezers. Cold appliances are estimated by the MTP to account for 19\% of UK domestic electricity use in 2005, with the majority of households owning at least one refrigerated appliance (MTP 2008).

For the purposes of modelling the MTP use an average percentage ownership of each cold appliance type (Defra 2008). However this is problematic if we wish to understand the ownership of appliances at the level individual house, because in practice households often own multiple cold appliances. Mansouri and Newbourough provided a more detailed breakdown of ownership patterns, shown in table 6.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fridge-freezer</td>
<td>32.0</td>
</tr>
<tr>
<td>Refrigerator and upright freezer</td>
<td>19.4</td>
</tr>
<tr>
<td>Refrigerator and chest freezer</td>
<td>9.9</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>8.2</td>
</tr>
<tr>
<td>Refrigerator and fridge-freezer</td>
<td>7.0</td>
</tr>
<tr>
<td>Fridge-freezer and upright freezer</td>
<td>4.9</td>
</tr>
<tr>
<td>Refrigerator, fridge-freezer and upright freezer</td>
<td>4.9</td>
</tr>
<tr>
<td>Fridge-freezer and chest freezer</td>
<td>3.5</td>
</tr>
<tr>
<td>Refrigerator, upright freezer and chest freezer</td>
<td>2.7</td>
</tr>
<tr>
<td>Refrigerator, fridge-freezer and chest freezer</td>
<td>1.5</td>
</tr>
<tr>
<td>Other combinations</td>
<td>6.0</td>
</tr>
</tbody>
</table>

\textsuperscript{36} A telephone energy efficiency adviser.
As mentioned earlier, cold appliances have been one of the success stories of increased efficiency. Table 7 shows the steady improvement of appliance efficiency since 1970.

### Table 7 Historic trends in average energy consumption at point of sale (Boardman, Lane et al. 1997; MTP 2008).

<table>
<thead>
<tr>
<th>Type/kWh per year</th>
<th>1970</th>
<th>1980</th>
<th>1990</th>
<th>1995</th>
<th>2008 (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fridge-freezers</td>
<td>730</td>
<td>659</td>
<td>626</td>
<td>601</td>
<td>412</td>
</tr>
<tr>
<td>Refrigerators</td>
<td>421</td>
<td>385</td>
<td>312</td>
<td>267</td>
<td>184</td>
</tr>
<tr>
<td>Chestfreezers</td>
<td>815</td>
<td>675</td>
<td>454</td>
<td>404</td>
<td>235</td>
</tr>
<tr>
<td>Uprightfreezers</td>
<td>881</td>
<td>725</td>
<td>489</td>
<td>423</td>
<td>243</td>
</tr>
</tbody>
</table>

These improvements have resulted in the energy use of cold appliances being reduced, despite the increase in households and hence appliances (Boardman, Lane et al. 1997). Cold appliances are, according to the 1997 Decade report, typically replaced after about 14 years service (ibid). More recent surveys suggest that the average age of a UK cold appliance is 5.1 years (Faber, Presutto et al. 2008). Using these data we can therefore assume that the UK’s cold fleet averages are somewhere between the 1995 and 2010 figures in table 7.

Electrical refrigerators and freezers both work by the same principal, that of the refrigeration cycle; a refrigerant fluid that is evaporated to effect cooling in an internal heat exchanger, and then compressed back to a hotter liquid which is cooled in an external heat exchanger (Trott and Welch 2000).

In domestic appliances the work of the refrigeration cycle is most commonly performed by a hermetic compressor, typically switched on and off by an adjustable thermostat (ibid). Since there is thermal latency in the system and thermostats exhibit hysteresis, the unit temperature tends to modulate above and below a ‘target temperature’.

Cold appliances have a number of design variants; traditional small refrigerator units have a single cooling element at the top which provides an ‘ice box’ and cooling for the refrigeration space; fridge-freezers typically having a larger freezer volume with a

---

37 All moving parts a contained within a sealed unit to avoid leakage.
separate door, have two evaporators and one compressor and larger variants are in effect two separate machines with two refrigeration circuits.

Catering food standard regulations require that certain foods are kept at or below 8°C and recommend that refrigerators operate at or below 5°C (FSA 2009). These numbers reflect the settings on a typical modern refrigerator compartment. Freezer temperatures are not subject to the same regulation but are typically in the region of -18.0°C and below. These numbers are consistent with the test conditions specified by the European energy label certification tests (MTP 2007).

The efficiency of a cold appliance is a function of two variables, the efficiency of the heat pump system, and the insulation of the storage volume. The energy use of a cold appliance is a function of its size, efficiency (as above) and its operating conditions.

The opening of doors and loading with food results in increased energy use. Various studies have reported figures in the range of 1-10% for door opening, and loading costs being determined by the food temperature. However the most significant issue is the temperature of the room where the refrigerator is situated (Faberi, Presutto et al. 2008). The room temperature has a two fold effect, firstly the warmer a room the more often the heat exchanger pump is active and a secondary order effect is that the warmer the room the less effective the external heat exchanger will be. Ideally cold appliances should be situated in as cool a location as possible with free air flow to the external heat exchanger. This is often not the case with fitted kitchen designs sometimes restricting air flow to the heat exchanger. Another potential issue is that the external heat exchangers can collect dust and this affects their efficiency (ibid).

Surveys have been conducted that show that many domestic cold appliances in operation are faulty (Boardman, Lane et al. 1997). Damaged seals, faulty thermostats, loss of refrigerant and compressor wear can all affect machine efficiency. The UK appears to have a culture of not servicing appliances, with 5% or less of appliances

38 The author identified a number of households where this was the case during the process of measuring appliance demand profiles.
having been serviced. However this is consistent with earlier replacement compared to other European countries (Faberi, Presutto et al. 2008).

Despite mandatory minimum standards and many cold appliances achieving an A rating, there appears to be significant technical potential for reducing cold appliance consumption. New approaches to the overall design of fridge-freezers have been developed, for example a return to a single heat exchanger approach where the refrigerator space is fan cooled with cold air taken from the freezer compartment. This results in the freezer compressor working closer to steady state, which is more efficient, and avoids the unnecessary cycling of a separate compressor, reducing energy consumption by over 30% (Pedersen and Sallo 2000).

Vacuum insulated panels (VIPs) represent a promising technology to improve cold appliance efficiency. Existing cold appliances use polyurethane foams to provide insulation, and VIPs have a thermal conductivity in the range of 3 – 7 times lower. VIPs are more expensive than current approaches, and refrigerators are very cost sensitive in the competitive market, but if mandated or made less expensive they represent an attractive solution because they do not reduce storage space as would, for example doubling the polyurethane insulation thickness (Manini 2000).

Polyurethane insulation has been shown to degrade through thermal ageing, especially in the first few years of service, with a five to seven percent reduction in insulation in years one to three respectively (Ozkadi 2000). VIPs would not suffer from this decline in efficiency unless they leaked. Beyond the appliance environment and its insulation, further improvements can be achieved through the design and operation of the heat pump system.

Cold appliance compressors typically use asynchronous single phase induction (ASPI) motors. Permanent magnet synchronous motors (PMSM) have been proposed as an alternative providing higher power factor and the absence of field losses (Parasiliti, Petrella et al. 2000). ASPI technology is said to be more appropriate for commercial applications where variable speed drives are used, but fixed speed designs are used for domestic application on the grounds of cost.
Other efficient motor configurations have also been developed, for example the Carbon Trust has funded the development of a ‘linear motor’ compressor, but the deployment of new technologies face significant barriers:

‘Despite the anticipated improvements in performance, the high cost sensitivity in the domestic refrigerator market remains a barrier to further development and commercial up-take of this technology. Disappointingly, currently there does not appear to be sufficient ‘market pull’ to justify investment in energy-saving technologies. This also applies to variable-speed (variable capacity) compressors which have so far achieved poor adoption over existing compressors due to the price difference. To date, no patent applications have been filed for the highly innovative technology which has been developed during the project, despite its financial and carbon saving potential.’

(CarbonTrust 2007)

Alternatively, voltage control electronics can be used to optimise the working efficiency of the traditional ASPI. Two problems exist with the operation of ASPIs, ‘design start ability criteria’ and ‘variation of working torque’ (Bianci and Martini 2000), and these can to some extent be corrected by dynamically controlling the voltage fed to the compressor motor. Similar technology is also available as an adapter device known as the ‘Savaplug’ which can be retrofitted to older appliances, with claims of reducing fuel bills (SAVAWATT 2009).

The physical properties of the refrigerant fluid used in the heat pump system are an important factor in heat pump efficiency. The banning of chlorofluorocarbons (CFCs) because of their effect on the ozone layer has lead to alternatives being adopted, commonly R134a or HC600a. These are problematic in that they are powerful greenhouse gasses, thus the search for an effective more environmentally benign refrigerant continues (Sattar, Saidur et al. 2007).

Sales of the A+ and A++ rated products are said to be only 8% of the market (MTP 2010), and this will need to be rectified if the MTP P1 scenario targets are to be met. The MTP P1 scenario requires that:
• 2010: 100% of sales of cold appliances are EU energy label A-rated or better.
• 2015: 100% of sales of cold appliances are A+ rated or better.
• 2020: Over 80% of sales for all cold appliances are A++ rated.

3.2.5 Wet

The Wet category refers to washing machines, clothes dryers and dishwashers. Wet appliances accounted for 16% of UK domestic electricity use in 2005. As with cooking appliances, the ESTs definition of wet appliances differs from that of the MTP and includes showers.

<table>
<thead>
<tr>
<th>Penetration of wet appliances</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dishwashers</td>
<td>25%</td>
</tr>
<tr>
<td>Tumble dryers</td>
<td>40%</td>
</tr>
<tr>
<td>Washing machines</td>
<td>79%</td>
</tr>
<tr>
<td>Electric showers</td>
<td>35%</td>
</tr>
<tr>
<td>Washer dryers</td>
<td>15%</td>
</tr>
</tbody>
</table>

3.2.5.1 Washing Machines

Washing machines require energy for four basic processes, heating water, agitating the load, spin drying and pumping waste water.

In the past it was common for UK washing machines to have a hot water as well as cold water feed, but this approach has fallen from favour despite the potential efficiency benefits of using gas to heat water. This may be because the EU labelling scheme does not reward hot water feeds and a hot feed requires additional components thus impacting cost. The lack of hot water feed also represents a reverse salient to those with solar hot water systems.

There are cases of UK appliance designs trading off wash temperature to achieve higher efficiency labelling. A confidential source in an appliance testing company reported that some machine 60 degree washes only reach 50 to save energy and thus achieve a desired energy rating.
The energy use per wash programme has fallen as a result of two factors, the decline in the use of hot washes, shown in table 9 and the improved efficiency of appliances, which now are almost all A rated, see table 10.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>40°C</td>
<td>177</td>
<td>179</td>
<td>186</td>
<td>187</td>
<td>187</td>
<td>187</td>
</tr>
<tr>
<td>60°C</td>
<td>90</td>
<td>89</td>
<td>83</td>
<td>82</td>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>90°C</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 10 Trends in washing machine temperature settings (MTP 2008).

<table>
<thead>
<tr>
<th>kWh/cycle</th>
<th>A+</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°C</td>
<td>1.66</td>
<td>1.77</td>
<td>1.77</td>
</tr>
<tr>
<td>60°C</td>
<td>1.00</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>40°C</td>
<td>0.60</td>
<td>0.64</td>
<td>0.64</td>
</tr>
</tbody>
</table>

No literature was found comparing the benefits of different washing machine configurations, for example top loaders used to be common, but the front loader design now appears almost universal in the UK. Large top loader washing machines are common in the US and appear to be more efficient in electricity use than EU designs. A long running trial of high performance, top loading machines machine showed an average electricity use of 0.2kWh per cycle compared to 0.26kWh for inefficient designs (Parker and Sullivan 2000). This number appears incongruous when considering the average EU machine consumes in the region 1.0 kWh per load. The machines in this experiment did however use a lot of water, 16 gallons for the efficient design and 36 gallons for inefficient design, and they use hot water feeds, but the difference in electricity demand is perhaps worth further investigation.

This disparity in resource use between different technology cultures highlights the potential for different approaches in machine design, thus our A and A+ rated appliances today may be far from optimal. For example, price often dictates technology options:
‘In general, currently available domestic washing machines employ one of four main types of motor, viz, universal motors, wound field dc motors, permanent magnet dc motors or single-phase induction motors. Heavy investment in these existing technologies and the prospect of high retooling costs, have prolonged the use of low cost machines which offer relatively poor standards of performance. Previously, the energy performance of the drum drive was not a primary design consideration, low motor efficiency being concealed by the energy requirement of the water heating element, which dominated the overall energy consumption.’

(Harmer, Mellor et al. 1994)

Literature on options to improve motor drives include using inline voltage control (Frattesi, Petrella et al. 2000) similar to those already discussed with reference to cold appliances, induction versus commutator motors (Harmer, Mellor et al. 1994), and more complex induction motor control (Zheng Zhang and Longya Xu 2006). Other research has identified the benefits of micro-processor machine management to optimise wash parameters (Mohammadi-Milasi, Lucas et al. 2005). Dedicated silicon chips are now available that contain all the control logic for a washing machine including wash performance optimisation (Freescale 2005).

Washing machines are now available (for example the LG F1222TD) that use steam instead of water to clean clothes although no literature was found as to the appropriate application and energy use of steam cleaning. This machine and others now also use direct drive motors, instead of the conventional belt driven approach.

In Japan a radical design has been announced that uses ozone for a type of ‘dry clean’ but these have not reached the UK market (McNulty 2006).

3.2.5.2 Tumble dryers

Tumble dryers use energy for heating and circulating air and turning the drum. As the drum rotates hot air is passed over the clothes and causes evaporation.
Because the drum is not filled with water and agitation is more continuous than with a washing machine, less energy is spent on the mechanical process. Tumble dryers do however use a great deal of energy heating air for the drying process. In an electrical tumble dryer this is done with a fan assisted heating element with hot damp air being expelled. Heat exchangers can be used to warm incoming air with heat from the exhaust, reducing energy loss.

According to MTP the average energy consumption per use is 2.50 kWh, based on tumble driers being used 148 times a year (60% of the number of times that a washing machine is used, for households owning a tumble drier.) Driers are owned by around 42% of households, with each tumble drier using an average of 354 kWh per year (MTP 2008).

<table>
<thead>
<tr>
<th>Mode</th>
<th>Max (W)</th>
<th>Min (W)</th>
<th>Average (W)</th>
<th>% of models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standby</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>‘On’ button engaged</td>
<td>4</td>
<td>1</td>
<td>2.6</td>
<td>38%</td>
</tr>
<tr>
<td>Delay timer operated</td>
<td>3</td>
<td>3</td>
<td>2.9</td>
<td>34%</td>
</tr>
</tbody>
</table>

Experimental research on improving tumble dyers appears scarce. Experiments have shown that the use of powerful ultra-sonic sound can significantly reduce drying time and reduce energy consumption (Khmelev, Savin et al. 2006).

**3.2.5.3 Dishwashers**

Dish washer perform three main processes that require electrical energy, heating of water during the washing process, pumping water to drive the spray mechanism and to expel water, and heating the air inside the machine to dry the load.

As with washing machines, modern dish washers tend to only have a cold water inlet where both hot and cold were once common. Some manufactures state that their machines can use hot water fed into the cold inlet as an energy saving measure. However this does mean that the initial rinse cycle will use hot water where as this process would usually be performed with cold water.
On some machines the hot air drying process can be turned off, reducing energy consumption, but this feature is not universal. This is a useful option if the user has time to wait for the load to dry ‘naturally’.

Like washing machines there has been a trend to lower wash temperatures, see table 13. The reduced temperature with better managed water use has had a significant effect upon the total energy used per wash. Average A rated appliance are shown in table 14.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>55°C</td>
<td>90</td>
<td>93</td>
<td>101</td>
<td>110</td>
<td>120</td>
<td>121</td>
</tr>
<tr>
<td>65°C</td>
<td>161</td>
<td>157</td>
<td>147</td>
<td>135</td>
<td>124</td>
<td>121</td>
</tr>
<tr>
<td>Total</td>
<td>251</td>
<td>250</td>
<td>248</td>
<td>245</td>
<td>244</td>
<td>242</td>
</tr>
</tbody>
</table>

Table 14 Average energy consumption of dishwasher settings (MTP 2008).

<table>
<thead>
<tr>
<th>Programme</th>
<th>kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>55°C</td>
<td>1.07</td>
</tr>
<tr>
<td>65°C</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Table 15 Typical standby in dishwashers (n=47) (MTP 2008)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Max (W)</th>
<th>Min (W)</th>
<th>Average (W)</th>
<th>% of models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standby</td>
<td>4</td>
<td>3</td>
<td>3.25</td>
<td>4%</td>
</tr>
<tr>
<td>‘On’ button engaged</td>
<td>16</td>
<td>1</td>
<td>2.7</td>
<td>70%</td>
</tr>
<tr>
<td>Delay timer operated</td>
<td>16</td>
<td>1</td>
<td>2.9</td>
<td>50%</td>
</tr>
</tbody>
</table>

No literature was found relating to technology options to increase dish washer efficiency, but ‘best available technology’ appliances use only 0.83kWh per wash (MTP 2006).

3.2.5.4 Summary
Wet appliances have shown improvements in energy efficiency and are not an MTP target for radical efficiency improvements. However there a range of technologies that could offer further improvements. Further reductions in wash temperatures may be seen with clothes washing but hygiene may be an issue with dish washing.

39 Dishwashers are assumed to use the same amount of water and energy regardless of how full they are loaded. Tests with full and part loads showed little difference in energy consumption. It is assumed that most 12-place dishwashers are only seven places full when used.
MTP scenario P1 requires that:

- 2010: 50% of washing machine sales are A+ rated, 25% of tumble dryer sales use heat pumps or similarly efficient technology and over 95% of dishwasher sales are A-rated.
- 2020: 100% of washing machine sales are A+ rated, 75% of tumble dryer sales use heat pumps or similarly efficient technology. Dishwashers using 15% less energy than the current A-rated products account for 70% of sales.

(MTP 2008)

3.2.6 ICT

The MTP ICT category includes monitors, desktop PCs, laptop PCs, printers, multi-functional devices (MFDs) and photocopiers. The recent widespread adoption of personal computers (PCs), spurred by the popularity of the internet now justifies ICT as a distinct category from ‘consumer electronics’. In the words of the MTP:

‘Overall there is strong demand for ICT products and development rates are fast, with ICT products accounting for 11% of domestic electricity consumption. Most in-use energy in the sector is consumed by desktop PCs and imaging equipment, representing areas where significant energy savings can be made.’

(MTP 2008)

The majority, over 80%, of ICT load is said to be due to computers, their monitors and imaging equipment. Given the significance of computer energy demand the UK government conducted a survey comprising energy monitoring and questionnaires relating to usage habits. The tables below show the typical usage patterns for PCs by the questionnaire correspondent.
Table 16 Own use of computer for work-related activities per week.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Frequency</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3hours</td>
<td>17</td>
<td>21.3</td>
</tr>
<tr>
<td>4-7hours</td>
<td>13</td>
<td>16.3</td>
</tr>
<tr>
<td>8-14hours</td>
<td>8</td>
<td>10.0</td>
</tr>
<tr>
<td>15-21hours</td>
<td>6</td>
<td>7.5</td>
</tr>
<tr>
<td>22-35hours</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>36-49hours</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>50-70hours</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>71+hours</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>Not at all</td>
<td>32</td>
<td>40.0</td>
</tr>
<tr>
<td>Don’t know</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 17 Own use of computer for non-work-related activities per week.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Frequency</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3hours</td>
<td>22</td>
<td>27.5</td>
</tr>
<tr>
<td>4-7hours</td>
<td>19</td>
<td>23.8</td>
</tr>
<tr>
<td>8-14hours</td>
<td>12</td>
<td>15.0</td>
</tr>
<tr>
<td>15-21hours</td>
<td>8</td>
<td>10.0</td>
</tr>
<tr>
<td>22-35hours</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>36-49hours</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>50-70hours</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>71+hours</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Not at all</td>
<td>15</td>
<td>18.8</td>
</tr>
<tr>
<td>Don’t know</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>100.0</td>
</tr>
</tbody>
</table>

These numbers reflect active usage of a PC and as such cannot alone be used calculate total ICT consumption since they do not include consumption when a PC is left idle or on standby.

In ICT the issue of unnecessary standby consumption is more complicated than with other appliance categories since computers support a range of energy saving options, whereby components ‘sleep’ to save energy but with delayed availability\(^{40}\). Figure 13 demonstrates a computer with three consumption levels, where lower power mode offers a compromise between the energy consumption of ‘active mode’ and the time spent to ‘boot up’ a machine from cold.

\(^{40}\) For example disk drives may need to spin up to speed.
Figure 13 Demand trend of personal computer (MTP 2008)

Despite their energy saving benefits, these features are only used by a small percentage of computer owners, most users being either disinterested or unaware of the options. The only option commonly used (over 50% of respondents) is the automatic turning off monitor after a preset idle period (MTP 2008). Options such as auto-hibernate or switching off hard-drives are rarely activated, with over 75% of these options not used when available.

Given the MTP analysis of the low adoption of energy efficiency settings these could be made mandatory default settings. All machines could be automatically shipped in the lowest energy mode, with suitable guidance, providing low cost demand and educational benefits.

Typical PC demand levels and durations taken from the Defra survey can be seen in table 18.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Minutes</th>
<th>Hours</th>
<th>% of day</th>
<th>Mean (kW)</th>
<th>Consumption (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainsoff</td>
<td>159.8</td>
<td>2.7</td>
<td>11.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>PCoff</td>
<td>899.6</td>
<td>15.0</td>
<td>62.5</td>
<td>0.003</td>
<td>0.045</td>
</tr>
<tr>
<td>Low</td>
<td>12.2</td>
<td>0.2</td>
<td>0.9</td>
<td>0.03</td>
<td>0.006</td>
</tr>
<tr>
<td>Active</td>
<td>368.4</td>
<td>6.1</td>
<td>25.6</td>
<td>0.079</td>
<td>0.485</td>
</tr>
<tr>
<td>Total</td>
<td>1440</td>
<td>24</td>
<td>100</td>
<td>0.536</td>
<td></td>
</tr>
</tbody>
</table>
A summary of the typical consumption of main ICT components is shown in table 19.

Table 19 Mean energy consumption for ICT components from surveys, A (Ross and Meier 2000), B (Rosen and Meier 2000), C (MTP 2008; MTP 2008)

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Standby (W)</th>
<th>Idle(W)</th>
<th>Active(W)</th>
<th>n</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave</td>
<td>Min</td>
<td>Max</td>
<td>Ave</td>
<td>Min</td>
</tr>
<tr>
<td>Phone</td>
<td>2.1</td>
<td>0.6</td>
<td>3.5</td>
<td>19</td>
<td>A</td>
</tr>
<tr>
<td>Cordless phone</td>
<td>2.6</td>
<td></td>
<td></td>
<td>30</td>
<td>B</td>
</tr>
<tr>
<td>Answer machine</td>
<td>2.2</td>
<td>1.8</td>
<td>2.9</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td></td>
<td>3.6</td>
<td>27</td>
<td>B</td>
</tr>
<tr>
<td>Fax</td>
<td>5.0</td>
<td>3.1</td>
<td>6.6</td>
<td>5</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>30</td>
<td>100</td>
<td>5</td>
<td>B</td>
</tr>
<tr>
<td>Mobile phone charger</td>
<td>1.0</td>
<td></td>
<td>5.0</td>
<td>7</td>
<td>B</td>
</tr>
<tr>
<td>Computer</td>
<td>1.2</td>
<td>0</td>
<td>2.3</td>
<td>8</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>80</td>
<td>125</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>12</td>
<td>8</td>
<td>A</td>
</tr>
<tr>
<td>Laptop</td>
<td>1.1</td>
<td>1.6</td>
<td>15.7</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Monitor</td>
<td>2.0</td>
<td>0</td>
<td>5.9</td>
<td>8</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>1.0</td>
<td>36.0</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Printer</td>
<td>4.2</td>
<td>1.7</td>
<td>11.5</td>
<td>6</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>3.6</td>
<td>12.1</td>
<td>361</td>
<td>4</td>
<td>B</td>
</tr>
<tr>
<td>Dotmatrix</td>
<td>0.00</td>
<td>13.0</td>
<td>15.5</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Inkjet</td>
<td>1.3</td>
<td>4.4</td>
<td>29.5</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Laser</td>
<td>13</td>
<td>135.6</td>
<td>554.5</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Subwoofer</td>
<td>6.9</td>
<td>4</td>
<td>10.8</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td>Laptop charger</td>
<td>4.5</td>
<td>1.1</td>
<td>19.6</td>
<td>7</td>
<td>A</td>
</tr>
<tr>
<td>Copier</td>
<td>5.1</td>
<td>0.3</td>
<td>9.8</td>
<td>2</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.8</td>
<td>3.1</td>
<td>366.6</td>
<td>1077</td>
</tr>
<tr>
<td>MFD Inkjet</td>
<td>2.7</td>
<td>5.1</td>
<td>29.5</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>MFD Laser</td>
<td>8.8</td>
<td>5</td>
<td>9.3</td>
<td>197.4</td>
<td>680.7</td>
</tr>
</tbody>
</table>

Besides the active power consumption of ICT equipment, it is worth noting that most desktop power supplies (switch mode power supplies) exhibit ‘constant power’ behaviour, that is as voltage falls their current increases. This behaviour is the opposite to resistive loads, for example kettles, which consume less power as voltage
falls\textsuperscript{41}. In order to drive down ICT demand the EU is proposing a phased policy approach similar to that used for white goods, namely labelling and choice, then enforced minimum standards. Where labelling schemes for white goods is a European scheme the voluntary Energy Star scheme to be used for ICT equipment is international, originating from the United States.

3.2.7 Consumer electronics

Consumer electronics include all electronic items other than ICT equipment. This category was previously called ‘brown goods’ referring to televisions, video cassette recorders and HiFi equipment. Table 20 shows the market penetration of the most common consumer devices.

Table 20 Ownership of some common consumer electronic products

<table>
<thead>
<tr>
<th>Penetration of consumer electronics</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassette players/radios</td>
<td>95%</td>
</tr>
<tr>
<td>Hi-fis</td>
<td>94%</td>
</tr>
<tr>
<td>TV</td>
<td>98%</td>
</tr>
<tr>
<td>VCR</td>
<td>87%</td>
</tr>
</tbody>
</table>

The pace of change with regards to consumer electronics makes statistics difficult to capture. For example, at the time of writing many VCR machines and CRT televisions are being discarded in favour of DVD and LCD equivalents.

Standby current is a common characteristic in electronic systems. Whilst analysts often criticise standby current as unnecessary waste, it can be considered as a corollary of the remote control. Firstly current must be consumed while the television awaits a signal from the remote control, and secondly the remote control removes the need to walk to the television where it can be turned off. This issue would not be a problem if the standby current was very low, but often the full power supply of an

\textsuperscript{41} Although they will consume roughly the same energy to boil a give quantity of water, since they will take longer to boil.
appliance is activated (with its associated losses), to provide the low current required to sense the remote control.

Solutions to the standby problem are commercially available, with various forms of remote control devices available that switch off power at the socket.

The International Energy Authority has proposed the ‘1 watt initiative’ aimed at driving all standby power to below one watt (IEA 2005). This obvious target for reducing waste has led to legislation for example in China, whereas the UK opted for a voluntary agreement approach similar to that seen with incandescent light bulbs (Defra 2008). However, again these approaches are to be superseded by European mandatory standards.

Many of the appliances discussed so far have many variants in use, from televisions to washing machines, and since all variants cannot be measured it is necessary to rely on data obtained from a sample group. An exception to this is in the communications sector where we find examples of ‘vertical integration’. For example in the UK satellite TV services are dominated by Sky, who control both the media and the means of communication, and this results in a widespread use of identical receivers. Ofcom, the communication regulator collects data on the use of such services and this allows us to have an accurate picture of TV services.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Users</th>
<th>% of households</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTT</td>
<td>17,307,000</td>
<td>97.78%</td>
</tr>
<tr>
<td>DTT+</td>
<td>393,000</td>
<td>2.22%</td>
</tr>
<tr>
<td>Total</td>
<td>17,700,000</td>
<td>71.66%</td>
</tr>
<tr>
<td>Sky</td>
<td>5,900,000</td>
<td>44.82%</td>
</tr>
<tr>
<td>Sky+</td>
<td>3,100,000</td>
<td>23.55%</td>
</tr>
<tr>
<td>Virgin</td>
<td>3,600,000</td>
<td>27.35%</td>
</tr>
<tr>
<td>Virgin+</td>
<td>262,400</td>
<td>1.99%</td>
</tr>
<tr>
<td>FreeSat</td>
<td>300,000</td>
<td>2.28%</td>
</tr>
<tr>
<td>Total</td>
<td>13,162,400</td>
<td>53.29%</td>
</tr>
</tbody>
</table>

42 DTT refers to digital terrestrial technology, the + suffix is use to denote recording capability (as per Sky products)
Table 21 lists the various digital TV technologies available in the UK circa 2008/9. The first two categories have a range of variants available on the market, where as the Sky and Virgin media technology is specific.

Similarly, games consoles are proprietary technologies. Table 22 shows estimates of ownership of the various alternatives, data is derived from internet journalist sources (Rankin 2004; spong.com 2009).

<table>
<thead>
<tr>
<th>Machine</th>
<th>Ownership millions</th>
<th>Percentage of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microsoft Xbox 360</td>
<td>3.9</td>
<td>15.42%</td>
</tr>
<tr>
<td>Nintendo DS</td>
<td>9.1</td>
<td>35.97%</td>
</tr>
<tr>
<td>Nintendo Dsi</td>
<td>0.3</td>
<td>1.19%</td>
</tr>
<tr>
<td>Nintendo Wii</td>
<td>5.4</td>
<td>21.34%</td>
</tr>
<tr>
<td>Sony PS2</td>
<td>2.5</td>
<td>9.88%</td>
</tr>
<tr>
<td>Sony PS2 slim</td>
<td>2.5</td>
<td>9.88%</td>
</tr>
<tr>
<td>Sony PS 3</td>
<td>2.2</td>
<td>8.70%</td>
</tr>
<tr>
<td>Sony PSP</td>
<td>3.3</td>
<td>13.04%</td>
</tr>
</tbody>
</table>

Like ICT devices, consumer electronics often exhibit different loads depending on their state. Table 23 lists a range of commonly owned devices, and their average consumption in a standby, idle and active modes.
Table 23 Average standby, idle and active consumption for a range of appliance types, A (Ross and Meier 2000), B (Rosen and Meier 2000), C (MTP 2008; MTP 2008) D (Owen 2007).

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Standby (W)</th>
<th>Idle(W)</th>
<th>Active(W)</th>
<th>n</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave</td>
<td>Min</td>
<td>Max</td>
<td>Ave</td>
<td>Ave</td>
</tr>
<tr>
<td>Clock</td>
<td>1.0</td>
<td>0.6</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clock radio</td>
<td>1.7</td>
<td></td>
<td></td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Analogue TV</td>
<td>6.4</td>
<td>2.5</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.6</td>
<td></td>
<td></td>
<td>75</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>116</td>
<td></td>
</tr>
<tr>
<td>Digital TV</td>
<td>8.8</td>
<td></td>
<td></td>
<td>177</td>
<td></td>
</tr>
<tr>
<td>LCD</td>
<td></td>
<td></td>
<td></td>
<td>148</td>
<td></td>
</tr>
<tr>
<td>Plasma</td>
<td></td>
<td></td>
<td></td>
<td>284</td>
<td></td>
</tr>
<tr>
<td>Set top box (STB)</td>
<td>10.2</td>
<td>1.5</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.4</td>
<td></td>
<td></td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>STB with recorder</td>
<td>11.3</td>
<td></td>
<td></td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td>Cable box</td>
<td>23</td>
<td></td>
<td></td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Satellite box</td>
<td>16</td>
<td></td>
<td></td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>VCR</td>
<td>5.3</td>
<td>1.3</td>
<td>11.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td></td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Digital Versatile Disk (DVD)</td>
<td>4.1</td>
<td></td>
<td></td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Stereo (component)</td>
<td>3.0</td>
<td></td>
<td></td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>Stereo (compact)</td>
<td>9.8</td>
<td></td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Stereo (portable)</td>
<td>1.8</td>
<td></td>
<td></td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>Receiver</td>
<td>2.8</td>
<td></td>
<td>8.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD Player</td>
<td>2.2</td>
<td>0</td>
<td>6.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tape Player</td>
<td>1.0</td>
<td>0</td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Games Console</td>
<td>1.1</td>
<td></td>
<td></td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>Microsoft Xbox 360</td>
<td>2.4</td>
<td></td>
<td></td>
<td>134.2</td>
<td></td>
</tr>
<tr>
<td>Sony Playstation 2</td>
<td>2.7</td>
<td></td>
<td></td>
<td>36.6</td>
<td></td>
</tr>
<tr>
<td>Sony Playstation 2 slim</td>
<td>1.2</td>
<td></td>
<td></td>
<td>21.8</td>
<td></td>
</tr>
<tr>
<td>Nintendo GameCube</td>
<td>0.1</td>
<td></td>
<td></td>
<td>22.6</td>
<td></td>
</tr>
<tr>
<td>Sony PSP</td>
<td>0.3</td>
<td>0.8</td>
<td>2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nintendo Wii</td>
<td>2</td>
<td></td>
<td></td>
<td>16.7</td>
<td></td>
</tr>
<tr>
<td>Sony Playstation 3</td>
<td>1.8</td>
<td></td>
<td></td>
<td>174</td>
<td></td>
</tr>
</tbody>
</table>
3.2.8 Miscellaneous

While many appliances logically fit into the preceding categories as discussed, there is a range of appliance that do not. Kitchen gadgets, vacuum cleaners and air conditioners are examples of such appliances and little data was found relating to their ownership or consumption. If we use the MTP or EST classifications, miscellaneous will necessarily contain appliances that would more logically lie in another category, for example food preparation gadgets. Table 24 shows some miscellaneous appliances identified by the EST, note that they include computers in this category.

<table>
<thead>
<tr>
<th>Miscellaneous</th>
<th>Ownership</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computers</td>
<td>45%</td>
</tr>
<tr>
<td>Personal care products</td>
<td>94% (hair care)</td>
</tr>
<tr>
<td>DIY equipment</td>
<td>59%</td>
</tr>
<tr>
<td>Home security systems</td>
<td>?</td>
</tr>
<tr>
<td>Vacuum cleaners</td>
<td>?</td>
</tr>
<tr>
<td>Telephones/answering machines</td>
<td>?</td>
</tr>
<tr>
<td>Garden equipment – including outside</td>
<td>?</td>
</tr>
<tr>
<td>Heaters</td>
<td>80%</td>
</tr>
</tbody>
</table>

3.3 Summary

Government reports and academic literature have identified the wide variety of the domestic appliances and provided estimates of average consumption, per use and per annum. Some loads, particularly those in the cooking and wet categories exhibit relatively high power flows in the order of 1 – 10kW, but are typically limited in duration. Conversely consumer and ICT categories are typically much lower power loads but consume significant energy due to being used for long periods and with standby mode used as convenient substitute for turning appliances off.

The metrics most commonly used to describe these appliances are kW and kWh, the former describing their instantaneous power and kWh their total energy use, as read at the meter. Except for a limited literature that explores domestic demand in detail, for example (Newborough and Augood 1999), little attention has been paid to temporal dynamics of power flows in the home. The appliances available today are not
radically different from those available before the appliance labelling schemes introduction. The elimination of the least efficient appliances has been a success but there are few signs of new innovations permeating into the mass market.
4 Social and behavioural aspects of electricity demand

The previous chapter described the energy use characteristics of domestic electrical appliances and outlined the aspirations of ‘market transformation’.

The appliances listed serve different roles in the home, some consumer goods offer entertainment, where others are used as substitutes for physical labour. Bowden and Offer classify this distinction as ‘time using’ and ‘time saving’, and identify differences in their rates of adoption and roles in society (Bowden and Offer 1994).

A significant difference between these categories is that ‘time using’ appliances, for example radios and televisions, tend to be adopted much more rapidly than ‘time saving’ appliances. For example in the US circa 1930, radios could found be found in over 90 percent of wired households, less than a decade after their commercial availability. In the case of washing machines, it took until 1950 to reach a similar level of adoption. Similar disparities in rates of adoption were also seen in the UK, but occurring later and growing more slowly, due to historic lower disposable incomes and the interruption in trends caused by World War 2 (WW2) (ibid).

Asking how today’s domestic energy culture came to be, Shove describes our increased demand as caused by the ‘Converging conventions of Comfort, Cleanliness and Convenience’ (3Cs) highlighting that demand for services such as laundry have increased by a factor of five over the last century (Shove 2002). The 3Cs are described as having a ‘ratchet effect’ that escalates consumption, new technology pushing out traditional systems (for example washing machines versus hand washing), and increased levels of the 3Cs themselves raising social expectations in a form of positive feedback.

The ownership of ‘time saving’ technology, for example washing machines and vacuum cleaners, has been steadily increasing over half a century and many are now owned by a majority of households. Contrary to the term ‘time saving’, the adoption
of these appliances did not lead directly to a reduction in housework. In fact the workload of middle class housewives had steadily increased up to the 1960s, with a decline in the use of servants, and importantly, increased levels of cleanliness: clothes were washed more frequently and vacuum cleaners led to more frequent floor cleaning. Where housework may have been a family activity, for example laundry, this was ‘devolved back to the housewife’ (Bowden and Offer 1994).

The rapid and broader adoption of the most common ‘time using’ appliances, over that of ‘time saving’ is explained as having a range of social causes. Time saving appliances do not have the same value for ‘status display’, and are often ‘tucked away’ out of sight. Media from radio and television also provide social cohesion, for example in providing subjects for conversation from which non owners are excluded. Time using devices are also said to provide ‘comfort’ and ‘stimulus’ with addictive qualities (Bowden and Offer 1994).

Further proof of Bowden and Offer’s observation with regards to the rapid adoption of time using technology can been seen with the recent growth of ICT related energy demand. However the time using/saving distinction is not perhaps so clear with ICT, as computer and internet activity can be used to both save time, for example avoiding a trip to the shops, or use time by, for example playing computer games. Another distinction with the internet is that it is now viewed as a necessity of modern life, as with electricity following WW2, with government now promising universal access (Wray and Robinson 2009).

Despite the broad adoption of similar appliances, surveys reveal wide variations in energy use between different households. This is thought to be caused by a range of factors, for example household size, income, and lifestyle, and making energy use for a given home difficult to predict (Jeeninga and Hugenges-Wajer 1999) (Pett and Guertler 2004).

While some domestic appliance efficiencies have improved, for example cold appliances, as demonstrated earlier, national residential energy demand continues to rise. This is due in part to the increased number of households and hence appliances,
increases in appliance ownership, and efficiency standards being negated by increased level of service\textsuperscript{43} (Hinnells and Lane 1996; Boardman 2004; MTP 2008).

Some argue that this increased service demand indicates a need to focus on ‘behavioural issues as well as technical factors’ (Hinnells and Lane 1996) whilst others argue that current appliance standards are too weak and minimum standards more effective than voluntary agreements (Boardman 2004). These arguments focus on distinct aspects of the wider electrical system; standards improve the appliance ‘fleet efficiency’ and represent a ‘fit and forget’ solution; energy efficient behaviour on the other hand relates to how we interact with the appliance once it is acquired.

The former approach is more straightforward in terms of policy delivery and represents the bulk of projected efficiency gains. However as will be discussed later the standards approach has shown signs of stalling. Whether or not this is the case, difficulty in achieving emission reduction targets is likely to increase interest in ‘behavioural issues’. However besides basic actions, for example turning unnecessary lights off, the notion of behavioural change becomes vague; what is it that people are supposed to do differently?

Social science critiques of the ‘demands side’ policy discourse, that of energy efficiency, measurement and information provision, warn of risks and negative side effects of the current approaches (Shove 2000; Devine-Wright and Devine-Wright 2005). For example, negative perceptions of the consumer can have an adverse effect on technology and policy:

‘An ‘Information deficit’ model of public knowledge (e.g. Wynne and Irwin, 1996; Lutzenhiser et al., 2001) can lead to a ‘fit and forget’ approach to energy demand technologies that is grounded in, and legitimised by, a perceived absence of knowledge, participation, or ‘care’ on the part of the energy user.’

(Devine-Wright and Devine-Wright 2005)

\textsuperscript{43} For example more clothes washing.
This framing of the consumer is also reflected in the debate surrounding smart meters, ‘reduced wastage’ being an often cited benefit. Whilst metering technology has been shown to have a number of other benefits, discussed throughout this thesis, these have appeared infrequently in government and regulatory communications. More wide reaching criticism suggests that the ‘increased transparency’ agenda may be limiting the framing of the ‘energy problem’ itself. Focussing on intangible metrics that have little relation to environmental impacts risks ignoring the opportunities and challenges of a broader socio-technical transformation (Shove 2000).

These concerns challenge both the objectives and the methods of the domestic energy policy debate as being overly focussed on technology and economics, with human behaviour presented as a ‘problem’.

4.1 Understanding attitudes and behaviour

As introduced above, a long running thread in energy policy discourse is that of domestic consumers in ‘information deficit’ whereby, if their energy use was better understood, consumers would adopt more efficient behaviour, closing the ‘energy efficiency gap’.

This narrative relies on the assumption of the ‘rational consumer’ who changes behaviour through choice, based on understanding and attitude. This can be the case but with caveats:

‘In general, attitudes tend to predict behaviour best when (a) they are strong and consistent; (b) they are specifically related to the behaviour being predicted; (c) they are based on the person’s direct experience; and (d) the individual is self aware of his or her attitudes.’

(Hilgard, Atkinson et al. 1996 )

44 This section is an adaption of text from Bilton, M. (2005). An exploration of the use of mass media to increase energy efficiency in the residential sector. CEP, London, Imperial College, MSc.

45 The energy efficiency gap refers to the difference between what is cost effective and what is actually implemented.
Outside the energy policy arena, the notion of ‘rational choice’ has been widely criticised as either being overly simplistic or fundamentally flawed. In ‘Motivating Sustainable Consumption’ Jackson provides a meta-analysis of these issues highlighting alternative models:

‘One of the messages that flows from this analysis is that consumers are a long way from being willing actors in the consumption process, capable of exercising either rational or irrational choice in the satisfaction of their own needs and desires. More often they find themselves ‘locked in’ to unsustainable patterns of consumption, either by social norms which lie beyond individual control, or else by the constraints of the institutional context within which individual choice is negotiated.’

(Jackson 2005)

Psychology literature then suggests other, stronger determinants to behaviour. The need for brevity does not permit a fuller review of social, behavioural and cognitive psychology, but some important themes are introduced below.

4.1.1 Habits

‘We know, as individuals, that we often seem to act instinctively, automatically, out of routine or habit, or driven by emotional responses that appear beyond control in certain situations. We also know – and have made the point above – that this sometimes occurs in spite of our best intentions to act otherwise……’

(ibid)

Habits are useful in that they avoid the need for a full ‘cognitive deliberation’ over ones everyday actions. Assuming a change in attitude to ones own behaviour, for old habits to be broken, requires repeated ‘presence of mind’ before the new behaviour itself becomes routine:

‘…….in any circumstances in which one is attempting to change one’s own behaviour (or indeed the behaviour of others) the transaction costs of rational
deliberation appear to be reversed by the existence of habitualised behaviour. A distinct cognitive effort is now required to overcome habitual behaviour,…..’

(ibid)

4.1.2 Social Influence

‘Most, if not all, human behaviour can only be understood if it is thought of as social in nature, that is, as being directly or indirectly bound up with and influenced by the behaviour of others.’

(Gross 1992)

Rather than being independent agents, behaviour that is expressed in society, family and peers to some extent determine the individual’s attitude and behaviour. A key idea to understanding social influence is the ‘social norm’:

‘A social norm is a generally accepted way of thinking, feeling, or behaviour that is endorsed and expected because it is perceived as the right and proper thing to do. It is a rule, value or standard shared by the members of a social group that prescribes appropriate, expected or desirable attitudes and conduct in matters relevant to the group…. (Turner 1991)’

(ibid)

Empirical research has demonstrated the powerful drive that people have to conform to the ‘social norm’ of the group. For example, early experiments involved groups of participants who where asked to make estimations based on various visual cues. With all but one of the participants being actors, who produced unrealistic estimates, the non actor will tend to adjust their estimate significantly towards the group average (Hilgard, Atkinson et al. 1996).

Weakly held attitudes do not motivate changes in behaviour, moreover ambiguity in attitudes of a social group can induce ambiguity of attitudes in the individual. The reason for this is not that we simply can’t make up our minds by ourselves rather common attitudes assist social cohesion, serving their social adjustment function:
‘…the actual content of beliefs and attitudes is less important than the social bonds they provide. To the extent that attitudes serve primarily a social adjustment function, they are likely to change if the social norms change.’

(Hilgard, Atkinson et al. 1996)

Whilst this might appear to represent a chicken and egg problem, in that the main determinant of individual change is a change in social norms, it also explains the rapid changes that can occur, sometimes described as ‘tipping points’ (Darby 2005).

4.1.3 Authority

As well as adhering to social norms of attitude and behaviour, individuals have a strong tendency to behave in compliance with authority. Experiments have proven our apparently innate tendency to comply with the demands of authority.

Again in an experiment using actors, Milgam conducted experiments where participants were made to believe that they were administering powerful electric shocks to an individual for the purposes of research into learning. The presence and direction of an ‘authority figure’ caused the participants to deliver what they believed to be potentially fatal electrical shocks to the subject:

‘Milgram suggests that the potential for obedience to authority is such a necessary requirement for communal life that it has probably been built into our species by evolution.’

(ibid)

A positive aspect of this is that the tendency for individuals to allow themselves to be guided by authority underlines the potential of the role of government institutions and legislation in leading societal change.

4.1.4 Influential minorities

Were attitudes and behaviour only a function of social norms and compliance to authority, society would perhaps not evolve as it does. Significant societal changes can be brought about by individuals who manage to persuade the group to adopt
different attitudes and behaviour. Such individuals have existed throughout history, like, for example Nelson Mandela. Hilgard et al. summarise research in this area, stating:

‘The general finding is that minorities can move majorities towards their point of view if they present a consistent position without appearing rigid, dogmatic or arrogant. Such minorities are perceived to be more confident and, occasionally more competent than the majority. Minorities are also more effective if they argue a position that is consistent with the developing social norms of the larger society.’

(Hilgard, Atkinson et al. 1996)

4.1.5 Cognitive dissonance

A commonly cited theory relating to the relationship between attitude and behaviour is cognitive dissonance theory developed by Leon Festinger in 1957 (Hilgard, Atkinson et al. 1996). Individual cognitions can be considered as, beliefs, values, attitudes and emotions, the human mind comprising a complex collection of cognitions.

The vast majority of cognitions are independent from one another, for example, liking chocolate does not interfere with the belief that you have been to Sydney Opera House. Such relationships are termed as cognitive irrelevance. If however, cognitions are mutually dependent, for example, you have just bought a chocolate bar, and you like chocolate, the relationship is cognitive consonance. Cognitive dissonance occurs when two cognitions are inconsistent. The inconsistency produces discomfort and the individual is subconsciously driven to remove or reduce the dissonance. In terms of a situation where there is a conflict between attitude and behaviour, dissonance can be removed by altering either attitude or behaviour.

One obstacle to behaviour change through persuasion is that individuals tend to change their attitude to fit their behaviour. This phenomenon can however, be used to change attitudes. For example, if a person is coerced into changing their behaviour, for example by authority, they are likely to change their attitude to fit their behaviour hence avoiding cognitive dissonance.
In Jackson's words:

‘Furthermore, the social psychological evidence suggests that some behaviours are not mediated by either attitude or intention at all. In fact the reverse correlation, in which attitudes are inferred from behaviours, is sometimes observed. This has important implications for motivating sustainable consumption, because it suggests that behaviours can be changed without necessarily changing attitudes first.’

(Jackson 2005)

Interestingly, if the penalty or reward used in coercion is large, then it is less likely to change of attitude. This is thought to be because the penalty or reward justifies the behaviour change without the need to change attitude (Hilgard, Atkinson et al. 1996).

4.1.6 Attitudes as defence mechanisms

We have already mentioned one function of attitudes, namely their social adjustment function, according to Hilgard et al. (1996) they also serve:

- Instrumental function, to express our fundamental desires to avoid punishment and gain reward;
- Knowledge function, to make sense of the world;
- Value-expressive function, to reflect our values;
- Ego-defence function, to protect us from anxiety or threats to our self esteem;

(Hilgard, Atkinson et al. 1996)

In the process of persuasion, if an individual is challenged regarding a genuine conflict between their behaviour and attitude, this is in effect a challenge upon their notion of self:

‘The self consists of all ideas, perceptions and values that characterize “I” or “me”; it includes the awareness of “what I am” and “what I can do”.’

(Hilgard et al. 1996)

In order to protect self-esteem, avoid anxiety and cognitive dissonance, an individual may adopt an attitude for its ego-defence function, to support their existing attitudes or behaviour, and hence their sense of self. The adoption of an attitude for its ego-
defence function can manifest in different ways, all of which are described as defence mechanisms (ibid). Freud lists seven such defence mechanisms; repression, rationalisation, reaction forming, projection, intellectualisation, denial and displacement:

‘Freud used the term defence mechanisms to refer to unconscious strategies that people use to deal with negative emotions. These emotion-focussed strategies do not alter the stressful situation; they simply change the way the person perceives or thinks about it. Thus, all defence mechanisms involve an element of self deception.’

( ibid)

4.1.7 Emotional Influence

Returning to Jackson’s meta-analysis:

‘Some attempts have been made to construct a theory of rationality in which reason itself – far from being a deliberative process – is viewed as a set of conditioned responses to patterns of learning laid down as ‘emotional markers’ in the body (Damasio 1994, 1999). Reason itself, in this model, is a construct of our emotional responses to situations. We make decisions on the basis of our cognitive responses to affective (emotional) states which are themselves the result of physiological triggers in the body, that are built up from both innate responses and learned behaviours reinforced over the history of the individual life.’

(Jackson 2005)

However rather than being a distinct approach to understanding behaviour, this model appears consistent with the notions of cognitive dissonance introduced earlier. An extract from a managerial psychology text provides a brief summary to the issues discussed in this section:

‘Man likes to think of himself as a rational animal. However, it is more true that man is a rationalising animal, that he attempts to appear reasonable to himself and to others’

(Aronson 1973)
4.2 Influencing behaviour through persuasion

The previous section introduced a range of factors that can determine behaviour and challenge the ‘rational choice model’. However, as seen in the advertising industry, the activity of persuasion is certainly not limited to rational arguments alone, instead a range of conscious and subconscious cues can be utilised to serve a communication objective. Persuasion can be divided into three broad categories: response shaping, response reinforcing and response changing (Jowett and O’Donnel 1986).

- Response shaping is a process where incremental changes in attitude or behaviour are reinforced through reward, in a teaching-like process.
- Response reinforcing is where existing attitudes or behaviour are reinforced to obtain an increased response in attitude or behaviour.
- Response changing, the category that can be most difficult to deliver, refers to changing attitudes and behaviour.

The common goal of energy related information is to change inefficient behaviour or reinforce efficient behaviour. In order to be effective, individual communication events must serve a specific objective; they must shape, reinforce, or change a specific attitude or behaviour.

Whichever category of persuasion a specific measure is designed to achieve, it needs somehow to tap into the pre-existing patterns of cognition in the audience. To do this, the audience must be understood in terms of its existing beliefs, values, attitudes and behaviour, as well as the norms of their social group. The persuader also needs to relate the required behavioural change to something the audience already believes in. This concept is known as ‘anchoring’; where a premise is attached to something already accepted by the audience and is used to tie down (to anchor) new attitudes or behaviour (ibid).

If climate change beliefs are not adequate as an anchor to change attitudes, energy efficiency has a number of other benefits:
• Saving money: this benefit is universally endorsed, since it is tangible, appeals to people’s self-interest and is common to all energy efficiency measures. However, it can take a long time for the initial investment to pay for itself and the savings are often difficult to quantify or too small to influence purchases, particularly those involving a high initial capital outlay.

• Improved comfort: this may be ‘a tangible benefit, although the reassurance that energy efficiency does not require people to make sacrifices in their lifestyle may be still more important’.

• Avoiding waste and the environment: this benefit is ‘less widely mentioned and more commonly associated with energy saving than energy efficiency. It is perceived as a moral obligation, particularly among older people and the struggling poor, with its roots in the way in which people were brought up. It has environmental connotations but in this context is more commonly linked with saving money [‘waste not, want not’].’

(Garmeson, 2002)

The process of persuasion is a two way process between two or more actors, thus also affected by perceptions about the persuader:

‘According to social learning theory, we learn most effectively from models who are attractive to us or influential for us, or from people who are simply ‘like us’. Sometimes we learn by counter-example. And we learn not to trust people who tell us one thing and do another.’

(Jackson 2005)

Thus even if we consider a ‘rational choice’ approach to persuasion, with the fundamental requirement being knowledge transfer, the process still depends on social and emotional cues.
Applied psychology provides some pointers as to how best facilitate knowledge transfer, stating that information is most effective when:

- attention grabbing (Gardner and Stern, 2002)
- presented frequently or backed up by reminders (Stern, 1999)
- credible and easily validated by the recipient (Becker and Seligman, 1978; Stern, 1999)
- trustworthy (Craig and McCann, 1978)
- about a specific rather than general environmental issue (Gardner and Stern, 2002)
- specific or tailored to the individual (Dennis and Soderstrom, 1988)
- involves social comparison with people similar to the target audience (e.g. Winnet et al., 1985)
- builds upon an existing commitment to act (Gardner and Stern, 2002)
- is delivered personally (Dennis and Soderstrom, 1988).

(Bilton, Ramsay et al. 2008)

These issues provide some guidance on the design of energy efficiency communications and utility billing, and to a lesser extent metering devices that display energy use in the home.

‘Visual display devices’ present additional issues because they are physical objects and present dynamic information. Norman identifies a range of design issues that affect the utility of every day objects, from door handles to hi-fi systems (Norman 1988). In describing ‘how people do things’ Norman develops a seven stage model, see figure 14 that provides some insight into the complexity of everyday actions.
Figure 14 Norman’s 7 stage model of behaviour.

If we consider a ‘visual display device’, it might be intended to improve ‘Perceiving the state of the world’, but the data provided by the device are only relevant when considered against the state of the consumer’s home, in other words, interpreting the perception. For example, reading a display that indicates our homes energy demand will only provide insight if we understand what appliances are currently switched on and we can make a connection between the metric and a specific appliance.

Once we have made a connection between a measurement and an appliance we might chose to act, but this is can also be hindered by misconceptions of the how the world works.

Norman classifies these two types of misconceptions as ‘The Gulf of Evaluation’ and ‘The Gulf of Execution’, and it is these gulfs that must be bridged if we wish to provide effective systems involving human interaction.
Familiar examples of ‘the gulf of execution’ can be readily found in the domestic setting. For example thermostats are often set too high in the incorrectly belief that the room will get warmer more quickly (ibid).

In summary, it should not be assumed that consumers understand the meaning of kW and kWh, nor should we assume that they know how appliances use energy or how much they use.

The issues raised in this section reiterate the complexities of conveying information and driving behavioural change, however effective methods of changing patterns of energy use have been identified in empirical research. The following two sections discuss two distinct categories of knowledge transfer used in demand side management, namely, consumption feedback and appliance labelling. The former aims to drive behavioural change through improved awareness of energy use, the latter changing ‘fit and forget’ purchasing decisions. The smart metering debate, reviewed later, has renewed interest in consumption feedback and its associated benefits, where as the labelling scheme represents a longer standing European policy.
4.2.1 Energy Consumption feedback to consumers

The notion that the ‘energy efficiency gap’ can be reduced by consumers being better informed about their energy use is a well established thread in the energy policy debate, although academic literature devoted to the subject is relatively scarce (Darby 2001). Literature focuses on empirical research involving sample populations stimulated with different information and communication methods, typically through billing or metering displays. Darby provides a meta-analysis of this work and provides a classification of forms of feedback, namely; direct, indirect, inadvertent, utility controlled, and energy audits.

From the limited studies available it appears that direct feedback, using devices that present energy use data in real time is the most effective individual mechanism, with most studies resulting in 5% or more energy reduction. In this category the top performing systems, achieving 20% reductions were ‘a table-top device’, ‘a prepayment meter’, and a meter designated for one appliance.

This suggests that keeping people informed of their energy use on a regular basis allows them to make significant behavioural changes. Direct feedback emerged as the dominant thread in UK ‘smart’ meter debate46, with most parties advocating ‘visual display devices’ that reflect frequent snap shots of instantaneous kW demand with cumulative historic kWh data.

Studies of feedback technology tend to focus on the aggregate demand of the household, however a small number of studies have measured the effect of feedback devices fitted to individual appliances. Wood and Newborough tested a range of methods to inform UK consumers in terms of their use of cookers, with accompanying antecedent advice (Wood and Newborough 2003). Combinations of information sources and feedback proved most effective, with up to a 39% energy reduction.

A similar experiment conducted in 10 Japanese homes, used a complex display, sub metering of individual appliances, and an uplink to the Osaka University (Ueno, Inada 2001).

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46 As observed at Ofgem and Adam Smith Institute meter events from 2005 – 2009.
et al. 2005; Ueno, Sano et al. 2005). Again by combining information and feedback total energy consumption was reduced by 12% and 19%. Both the UK and Japanese experiments produced a wide variety of effects, although on average positive, the best results were achieved when feedback was combined with advice. This is consistent with a narrowing of Norman’s ‘gulf of evaluation’ in using the meter display, and the ‘gulf of execution’ thought the specific antecedent advice, on for example cooking methods.

*Indirect feedback*, for example increased billing frequency, also appears effective, although less so, but does have the benefit of being low cost. Wilhite et al. experimented with different approaches to the presentation of billing information and revealed the benefits of including social cues to aid demand reduction. By representing household energy use in comparison with other local households, demand was reduced in high use households (Wilhite, Hoivik et al. 1999), indicating an indirect form of social influence, as discussed earlier in this chapter.

*Inadvertent feedback* includes the effects of social stimuli that are difficult to measure. Darby notes the possible benefits of social learning through community energy projects and the effects of micro-generation on individual energy use. These examples pertain to the ‘environmentally concerned’ or ‘energy literate’ and as such are not normative, however common social beliefs and attitudes do have a strong effect on the individual, as discussed earlier. Another inadvertent effect can be seen with the adoption of micro-generation. Research has shown ownership of micro-generation to have a positive effect on energy use behaviour in lowering demand (6%) and reducing peak demand, described as the ‘double dividend’ of micro-generation (Keirstead 2007). Qualitative evidence also suggests that householders will to some extent co-coordinate their energy use with the availability of a micro-generation resource:

> ‘When that red light is on we know we are exporting to the grid – so it’s time to put the washing machine on or it’s OK to boil the kettle. When that light is not on we make sure that everything is off – nothing is on standby because we know that it’s probably really costing us.’

Older couple, SW Lancashire with wind Turbine (SDC 2006)
Utility controlled: From a practical perspective, energy suppliers are well placed to offer complementary energy services since they are in regular communication and have a steady revenue stream from customers, they measure energy use⁴⁷, and can implement tariffs to include other services. However the energy providers ‘monopolistic’ role in energy service provision is problematic. As introduced earlier, a positive relationship between the communicator and the recipient in important. Positive or negative attitudes held by the recipient frame the process of knowledge transfer. Moreover limited perceptions about the consumer will frame the methods and content of the communication. Research has shown that consumers respond differently to identical communication delivered by different parties, with for example the ‘local authority’ being 25% more effective than ‘the energy retailer’ (Devine-Wright and Devine-Wright 2005). Qualitative research conducted for UK regulator Ofgem confirms that the relationship between suppliers and their customer is problematic:

‘Considerable scepticism about suppliers’ motivations has led to a trust deficit which may be difficult to overcome’

(Opinion_Leader 2009)

This suggests that the provision of energy services should not be restricted to the incumbent energy suppliers and questions their being ‘best placed to understand their customer’s needs’ as stated by Ofgem (Ofgem 2006). A separate agent may be better suited to informing consumers and delivering efficiency measures. More-over, in order to promote substitution, efficiency measures should be in competition for revenue from existing fuel budgets.

Energy Audits: have recently become a part of UK government endorsed supplier activity under CERT reflecting the adoption of processes similar to those used in the commercial and industrial sectors. In the C&I sectors energy audits are typically conducted by in house energy managers or consultants, not energy suppliers. The utility companies having responsibility for energy audits raises the issue of impartiality and trust already discussed.

⁴⁷ Although estimates are common.
4.2.2 Appliance Labelling

The labelling of goods under the European Energy Labelling Directive provides consumers with comparative information on the energy efficiency of appliances at the point of purchase, shown in figure 15.

![Energy Efficiency Label](image)

Figure 15 The UK version of the EU energy efficiency label (EST 2008).

Most appliances are rated between ‘A’ and ‘G’, but the most efficient cold appliances can now be identified by ‘A+’ and ‘A++’ (EST 2008). By law the Energy Label must be displayed on all appliances types listed below, that are for sale or hire:

- Refrigerators, freezers and fridge-freezer combinations
- Washing machines
- Electric tumble dryers
- Combined washer-dryers
- Dishwashers
- Lamps
- Electric ovens
- Air conditioners

The appliance rating is not an absolute measure of energy consumption; rather it reflects the relative efficiency of similar models. In the case of a refrigerator the rating
comparison is derived from energy used in the standardised tests and storage volume (MTP 2007).

The labelling scheme currently excludes consumer electronics and ICT products, but efficient ICT products can be identified by the voluntary Energy Star endorsement (under review in 2010), originating in the US, but now becoming an international standard. The Energy Saving Trust also has an endorsement scheme which can be applied to any product. Both endorsement labels are shown in figure 16.

![Endorsement type labels](DirectGov2008)

Both comparative ratings and endorsements are problematic in that they do not represent an absolute indication of energy use. Comparative labelling means that, for example, a large refrigerator using more energy than a smaller one, still achieves an A rating. A corollary of this is that the energy labelling scheme does not encourage us to choose smaller appliances. The labelling scheme is generally accepted to have been a success, but has in recent years received growing criticism and the EU label schemes are currently under review. Issues relating to the current scheme include:

- Labelling has been a victim of its own success with ‘crowding’ in the A rating. Whilst the labelling scheme has driven manufacturers to achieve A ratings, now that the majority appliances for sale are A rated there is consequently little differentiation (ANEC 2008)

- Self certification can result in wide variations of test results due to test environments. Sluis has demonstrated for example that different labs produce different results, showing a 17% variation for fridges, and 13% for freezers. (Sluis 2000)
Testing methods have been criticised for being unrealistic, for example fridge tests do not involve opening the door, instead the ambient test temperature is raised to 25°C (Morretti 2000).

Low sales of A+ and A++ cold appliances, at 3.8% of sales in 2008 (Defra 2008) suggest that either these higher bands are not effective at influencing behaviour, or that A sales are largely due to the crowding mentioned above. Experience in other countries suggest that existing top ratings, for example A do tend to stick in peoples minds despite newer improved ratings (Harrington 1997).

The calculation of CERT credits is managed by Ofgem, who have tightened the schemes specification recognising for example, the lack of benefit from A rated appliances, instead promoting A+ and A++ (Ofgem 2008)

‘Rolling’ standards, by which rating bands improve as average standards do, could address the crowding issue, but these have been resisted by manufacturers who claim they would require retesting and unnecessary costs (CECED 2007). This argument appears spurious since new ratings could be derived from metric data used in old tests, for example kWh/ per kg washed in the case of washing machines.

The appliance manufacturer organisation CECED has proposed an alternative open ended scale, using numbers from one upwards, but an adaptation of the current A-G scheme is more likely given its publics recognition (ANEC 2008). CECED has publicly resisted mandatory standards until there is an international agreement on the argument that it would impact on competition (CECED 2007).

While problematic, perhaps the greatest achievement relating to the labelling scheme is that it allowed the identification and regulation of the least efficient appliances. If the labelling scheme is to continue to drive efficiencies then there needs to be competition for the best grades. Furthermore Boardman et al. identify issues with the wider system that are necessary to support the labelling scheme:
‘An energy label is the necessary precursor for most other policies and provides useful information for consumers, but its maximum effect depends upon informed and supportive retail staff. The range of appliances stocked by retailers can only come from the models manufactured, but is strongly influenced by perceived consumer demand. The manufacturers respond both to legislative requirements and customer preferences. This circle of influences has yet to become properly established and powerful.’

(Boardman, Lane et al. 1997)

Whilst appliance ratings give an impression of relative efficiency, information about the importance of how appliances are utilised is typically not provided. For example cold appliance energy demand increases if:

- The temperatures are set unnecessarily low.
- Appliance is situated in a warm environment (Lebot, Lopes et al. 1997).
- There is restricted air flow to the heat exchanger (EEI 2006).
- The heat exchanger gets dusty (ibid).
- If warm food is not left to cool before loading (ibid).

The Edison Electricity Institute offer 100 similar tips in their document ‘100 ways to improve your electricity bill’ (EEI 2006). For many appliance types there would appear to be potential efficiency improvements though consumers being made aware of the importance of such placement and utilisation issues. This challenges the notion of ‘fit and forget’ approaches as a universal model for promoting appliance efficiency.

**4.2.3 Alternative approaches**

Before endorsing a continuation of the economic-technical perspective of measurement and efficiency, it is perhaps worth considering the potential for alternative models.

The discipline of traffic management has a tradition of metrology and technological interventions, consistent with its associated risks and the responsibilities of the state.
One successful practitioner of an alternative paradigm in traffic management was the late Hans Monderman, a Dutch traffic engineer who challenged the conventions of traffic management (Monderman 2007). Monderman identified the negative side effects of traffic control measures in towns and cities. He found that by removing traffic controlling measures, drivers behaved more responsibly and average speeds where reduced.

The incumbent paradigm, that of removing trees to increase visibility, the cluttering of the landscape with ‘street furniture’ such as signposts and speed cameras can cause ‘information overload’, encroach upon the space that is primarily intended for human use, and **unintentionally disengages the driver**. Monderman’s approach contrasts starkly to conventional enforcement measures, such as the speed camera, but as Birch highlights, technology has also provided successful tools for traffic calming. The graph below demonstrates the effect of different interventions with the objective of lowering traffic related deaths.

![Figure 17 Traffic related fatalities in Australia (Birch 2003)](image)

Here we see three technologies, radar, breath-testing and speed cameras, all forms of metrology used to good effect to achieve social objectives. As this example
demonstrates, there are not necessarily clear right or wrong approaches, rather social and technical approaches can help to achieve policy objectives. However we must remain aware that the effects of policies and technology on the wider socio-technical system can be dramatic, manifold and difficult to reverse.

The alternative to metrology in the electricity sector then might be a removal of meters and a return to localised energy production, as advocated by, for example Patterson, whereby all our energy needs are met locally and the wider system becomes irrelevant (Patterson 2007). However, a completely decentralised paradigm seems unlikely in the near future. The difficulties in making a transition to a low carbon economy are likely to require a culture of measurement akin to commercial and industrial energy management culture.

Furthermore it would appear that accurate data measurement is crucial for both social and technical transformation processes: The management of electrical systems development will be an important activity for government in the coming decades, since a significant transformation of all energy systems, will be required to achieve CO₂ emission targets.

The management of LTSs can involve a range of interventions in pursuit of a range of objectives. However, even when objectives are clear, for example ‘reducing CO₂’, their complexity means there is a great deal of scope for error and unintended consequences. While historians such as Hughes (Hughes 1983) retrospectively explain why and how systems develop, the complexity of large systems make it difficult to project any future development pathways.
4.3 Summary

From a policy perspective the domestic consumer appears to be poorly understood: while implicitly criticised for inefficient behaviour, little evidence or advice is provided as to what consumers should be doing differently, except for generic appeals to change light bulbs or turn down the thermostat.

Changing the behaviour of individuals, without the use of compulsory measures is difficult. Behaviour is largely dictated by social norms and habit, and largely a subconscious process. Generic approaches are likely to be limited in their effect since communication methods and content are most effective when tailored to the individual. Energy suppliers are in a weak position to conduct such activities due to a lack of trust and suspicion about their motives. Current policies rely largely on the labelling scheme, which grades appliances against current norms as opposed to promoting innovation. By providing a fixed grading scheme, standards are in a sense, frozen in time, with for example the A rated washing machine being no better now than when the scheme was introduced. The appliance labelling scheme might be described as a ‘market transformation failure’ in that it has not provided sustained development of new approaches to appliance design.

The labelling scheme comprises aspects of all 3Ms, measurement techniques involve a specific controlled ‘model’ environment and management is framed by the grading and labelling. The label then represents a cue for the consumers to create a mental model of the world.

Given the failings of the current appliance labelling scheme, some change to demand-side energy policy will be needed to provide a longer term trajectory to 2050 targets. However there are clearly opportunities for existing technology to be more widely adopted, particularly CFLs and this is reflected in recent approaches to restrict the availability of incandescent bulbs.

One apparent omission from policy is the lack of promotion of fuel substitution, specifically from electricity to gas, where available. Gas is gaining popularity for
hobs, but falling from favour in oven usage. Moreover, the labelling scheme, which does not account for the benefits of hot water feeds to wet appliances, discounts the benefit of using gas or solar heated water. In other words the labelling scheme in a sense works against overall carbon efficiency while promoting electrical efficiency. Here we see, in what will emerge as growing thread in this thesis, is that system efficiency is not simply the aggregate of individual appliance electrical efficiency ratings.

Moreover, returning to Hughes’ notion of systems, the metrics and models used, in for example the appliance labelling scheme, affect the perceptions of policy actors, consumers and technology development itself. In ‘Sustainability, system innovation and the laundry’ Shove makes a similar observation:

‘There is some merit in viewing the laundry as a large (socio) technical system akin to electrification (Hughes 1982), or the telecommunications infrastructure (Fisher 1992). In these cases too, the integration of constituent elements is critical to the operation of the system as a whole. The difference is that there are no obvious ‘system builders’ of laundry: no key institutions enlisted and enrolled and no well defined stages of socio-technical development’

(Shove 2002)

Further analysis might demonstrate closer similarities between the complex evolutions of electrification and laundry systems. For example, machine configurations are affected by both the designers of technology and policy makers, with for example, the effect that labelling has on appliance design. As was highlighted earlier the washing machine labelling scheme does not promote hot water feeds, and this feature has largely been lost. Furthermore, in practical terms, when plugged in, the washing machine actually becomes part of the physical electricity system, thus the process of electrification and ‘systems’ evolution to some extent includes the history and development of laundry processes.

Looking beyond current approaches, there appears to be potential for significant emission reductions though the use of feedback devices as part of a wider information system. Although the subject has not been extensively investigated, feedback can be
effective in reducing energy use. Moreover, given the subtleties of influencing behaviour there may be potential to improve the feedback effect, in what have appeared to be less responsive households. In other words, whilst there might be limits to what can be achieved with feedback, targeted and personalised systems may be able to change the behaviour of a wider set of consumers. There may also be potential for appliances, feedback systems, and the wider system to co-evolve yielding additional benefits, as yet not considered.

As ‘primary wastage’ in the existing system is reduced, due to the elimination of the least efficient appliances and wasteful behaviour, new avenues of improved efficiency will need to be discovered, evaluated and implemented.

In terms of shaping buying habits there remains a need for complementary information, for example, the appliance labelling schemes. In this respect metrics and media need to be aligned so that they can be understood in the wider context and in relationship to each other. In other words, smart meters and appliance labelling are components in the wider system and as such need to be compatible.

In the following chapter we move from the ‘demand side’ to the ‘supply side’ and examine how these aggregated loads interact with the wider electrical system.
5 The ‘Supply Side’: From generators to the meter

5.1 Power generation

Figure 18 represents recent trends in the fuel commodities used for the supply of electricity in the UK. Nuclear generation has declined as old stations are decommissioned and coal and gas dominate the remaining mix. The balance of coal and gas generation fluctuates depending on the available plant and prevailing fuel prices.

As has been demonstrated in the previous chapter, demand side measures targeted at the domestic sector have historically been focused on ‘fit and forget’ static measures such as thermal insulation and more recently compact fluorescent lights (CFLs). Using a passive/active-static/dynamic classification (Bilton, Ramsay et al. 2008) we can identify these measures as passive-static measures. These measures save energy without any change in consumer behaviour, i.e. passive, and do not respond to wider system conditions, i.e. static.
While the full technical benefits of these measures is often not realised, with for example room temperatures being increased when insulation is fitted\(^{48}\), they are generally considered to have a net benefit in terms of energy use as ‘read at the meter’.

Government departments often quote the carbon intensity of electricity supply as 0.4308 kg per kWh (OPSI 2008), however in practice the carbon emissions associated with electricity use depend on a number of factors. In practice this number will fluctuate according to fuel mix, losses, and the need for reserve capacity. ‘Spinning reserve’ is a term used to describe plant that is immediately ready to dispatch increased power to the system. This is typically provided by power stations running below maximum output. Figure 19 represents the UK’s total electricity demand and the mix of generation throughout a winter’s day in 2005.

![Figure 19: Electricity supply mix for one UK winter day’s (nationalgrid, 2006)](image)

What plant operates when depends on the national demand and the market behaviour of the various generator operators. At lower levels of demand, many plants are available and unless under repair the most cost effective plants will be dispatched. As

\(^{48}\) A direct form of the ‘rebound effect’.
demand increases so less plant is available and less efficient generators are brought on line.

Electricity market data are now available via the internet which describe both the real-time and historic price tends and commodity balances. An NGO called ‘realtime carbon’ has recently developed software that calculates an estimate of the carbon emission associated with a unit of electricity in real time (Realtime_carbon 2008).

Figure 20 Estimated carbon intensity curve for 1/12/2009.

Figure 20 shows one day’s estimated carbon intensity curve for a winter week day, namely Monday 1st December 2009. Here we can see the carbon intensity of electricity use is considerably higher than the stated annual average throughout most of the day. These data are estimated since they do not include the dynamics of losses or spinning reserve, but they do give us a clear indication of how the use of averages for carbon intensity can be misleading.

The majority of energy trading is through bilateral agreement; generator dispatch is pre-planned based on demand forecasts and all bilateral trading stops one hour before dispatch. Any difference between the pre-traded positions and forecast demand is managed by the system operator who holds contracts with generators to reserve capacity for the purpose of system balancing (Robinson 2003).
5.2 Demand response

In the UK, commercial and industrial consumers can participate in the electrical power market by adapting their energy demand to minimise costs. Adapting a load profile depending on market signals is commonly called ‘demand response’ and this comprises three broad categories of activity:

- time-varying pricing
- interruptible and voluntary load reductions
- customer provision of ancillary services

These measures can be used alone or in combination to serve objectives of price response, increased efficiency and security of supply. The following sections describe each category in more detail.

5.2.1 Time varying pricing

Time varying pricing refers to pricing mechanisms which reflect the energy wholesale market cost variation. Faruqui et al. (Faruqui, Chao et al. 2001) identify three approaches to time varying pricing:

- Real time pricing (RTP) refers to systems where consumer prices are regularly updated to reflect wholesale market cost. This is typically done on a day to day basis with diurnal price variations encoded in the time of use metering tariffs as described below.

- Time of use (TOU) tariffs reflect the average wholesale cost for different periods of the day, typically using hourly or half hourly (HH) meters. Unlike RTP, prices are predetermined for a contractual period, but do reflect average diurnal variations. Participating customers can then load shape to minimise demand at peak times and therefore lower their average costs.
• Coincident peak pricing (CPP) provides a simplified hybrid of the two previous categories. Typically two or three averaged price points are calculated to reflect different market conditions and the consumer is informed in advance of peak periods (for example specific hours or days). Peak periods are typically limited in number thus allowing participation without excessive risk.

Examples of the above can be found in the industrial and commercial sectors with customers able to choose a tariff that suits their demand flexibility and exposure to price risk. For example a large industrial operation might be able to benefit from RTP if their energy use is not time critical, for example heating systems with high thermal latency. Time of use pricing is more common and allows consumers to mitigate their average energy process without full exposure to market volatility.

In the domestic setting these mechanisms are less common. In the UK domestic electricity market Economy7, a simple TOU tariff, provides two rates; a low night time rate commonly used for space and water heating; and a daytime rate which is typically a little higher than the standard tariff.

Recently in California, concern about peak capacity has renewed interest in demand response and trials of a novel critical peak pricing system are being undertaken. Perhaps in keeping with Californian sensibilities, the utility has developed a novel feedback device that indicates approaching peak prices:

‘The orb flashes during the two hours before a ‘critical peak’ with high unit costs, and users who tried it out tended to reduce consumption well in advance of the peak and to continue with the reduction for some time afterwards. As a consequence, there was some overall saving as well as load-shifting’.

(Martinez and Geltz 2005)

In France, a similar approach differentiates critical peak days. Under the Tempo tariff, a visual indicator informs the user of the next day’s tariff; red, white or blue, with red being a critical peak day tariff limited to a certain number of days a year. This system follows a long standing culture of demand management in France, due in part to the
nation’s reliance on nuclear power. Nuclear power plants cannot readily modulate their output to the same extent as some fossil fuel plants, and as a consequence the French system benefits from a flatter demand profile.

In addition to TOU and CPP mechanisms, French domestic electricity tariffs typically vary depending on supply capacity to the home, which if exceeded causes supply to cut-out. This mechanism, which can be facilitated with the use of a simple bimetallic contact breaker, forces consumers to consider their aggregate load and thus flattens individual and aggregated demand curves. Whilst much of the debate on demand response tends to focus on more complex approaches, it is worth noting the effectiveness of this relatively simple measure.

5.2.2 Interruptible and voluntary load reduction

Voluntary load reduction programmes typically involve bilateral contracts in which customers reduce demand by a known quantity for a defined period. These contracts are typically prepaid with significant penalties for non compliance (EEI 2005).

In the UK, larger industrial customers can chose to contract to reduce load voluntarily during the winter ‘triad’ super peak periods, where electricity is priced at a significant premium. A peculiarity of this system is that triad periods are defined after the event and thus the demand response is to some extent a gamble (Custance-Baker 2006). In an extension to the common use of theEconomy7 scheme, the teleswitch is used by companies in Scotland (Scottish_Hydro 2008), to control heating loads remotely in response to weather and local system conditions:

‘Radio teleswitching is also used in the Company’s Southern Electric area to control demand within the capability of the power system and has done so since the technology became available in the mid 1980s. This approach to load management is particularly important in the less populated regions of the territory, where gas penetration is low, the volume of electric space/water heating is high and the distribution network is less robust.’

(SSE 2008)
Local control can also be used to reduce localised infra-structure costs for example using ‘ripple control’ to avoid peak load. Ripple control is where a number of loads draw power sequentially, using remote control, to avoid unnecessary peaks (Berghe and Pettersson 1993)\(^{49}\).

5.2.3 Manual intervention versus automation

Demand response is often characterised as being either behavioural or automated; however there is a range of levels of participation from manual to automatic, with different services suiting different approaches.

Full real-time pricing of electricity is not necessary to achieve much of the benefit of demand response. As the national diurnal demand curve is relatively predictable, TOU tariffs can reflect half hourly (HH) system prices and provoke appropriate responses. However unless TOU prices are updated daily, they cannot facilitate demand response to events such as critical peaks where supply is scarce and expensive.

Where TOU pricing records energy for fixed, typically HH time slots, critical peak systems record the energy use for different tariffs and the tariff period is changed dynamically. Critical peak pricing systems use remote control (say radio or PLC\(^ {50}\)) to signal tariff changes to consumers, but participation can be manual or automated.

Loads that have thermal latency like heating and cooling systems can be remote controlled without the user being inconvenienced, provided that temperatures are kept within acceptable limits. Conversely, services such as lighting and entertainment have less scope for automated demand response.

Other loads, such as wet appliances, can be deferred or paused automatically but it is likely that under certain circumstances customers may want to be able to override any such control; for example needing some clothes cleaned urgently. Load control

\(^{49}\) These systems rely on the loads being overrated for continuous operations, in other words they are not required to be on continuously.

\(^{50}\) Power Line Carrier.
technology can be facilitated in the absence of metering but if participation is optional as suggested above, then **metering is required to reward participants**.

In schemes that use critical peak pricing, consumers typically report that they would prefer options for automated load shedding as opposed to purely voluntary load reduction (IEA, 2005).

### 5.2.4 Ancillary services

Besides energy trading schemes as mentioned above, a range of other services are necessary for the day to day operation of power systems and preparation for emergencies (nationalgrid 2008):

- Reactive power must be ‘produced’ to serve demand and support system voltages\(^{51}\).
- Short Term Operating Reserve (STOR) is plant capacity, typically in large running generators, typically reserved for maintaining system frequency.
- ‘Fast start’ capacity is plant that is maintained for periodic use and started from standstill. ‘Black start’ capabilities must be maintained and tested to ensure system recovery in emergencies.\(^{52}\)

The reactive power market managed by the systems operator is used to support voltage on the transmission system as opposed to providing reactive power to consumers. Reactive power ‘used’ by consumers is paid for through distribution system costs and in larger C&I customers it is metered and charged for in addition to active power.

In organisations where the costs of reactive power flow are significant, energy managers can invest in compensation equipment where it is economic. While this

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\(^{51}\) Explained in more detail in chapter 11.

\(^{52}\) ‘Black start’ capability is a service whereby power stations can start-up from cold without the need for an external power supply. Whilst rarely if ever used, this service is essential in the case of total system failure.
does not significantly affect the active power load shape, it can be considered a form of demand side management.

While system demand is said to be met by supply, small ‘imbalances’ in supply and demand are reflected in the AC frequency (averaging at 50 Hz in the UK), which if falling indicates the need for more supply and visa versa.

The system operator holds contracts with generators to modulate their output, and large consumers to shed load, in order to maintain frequency within regulated limits. Some industrial customers are contracted to shed load automatically by remote control or under preset system conditions, for example if the system frequency falls below its regulated limits. Although these events can be rare, load-shedding can provide a very rapid response, which is very valuable to the system. Industrial load-shedding is well established, but research is ongoing into how the domestic sector could facilitate such services. For example ‘dynamic demand’ technology is being investigated where refrigerators switch on and off depending on system frequency, replacing the need for STOR (Infield, Short et al. 2007).

5.2.5 The benefits of demand response

In a free market, response to price is considered to be an important mechanism to govern demand (Hunt 2002). The lack of response engendered by flat tariffs has a number of effects on the market, namely:

- Unnecessarily high peaks in electricity price benefiting some generators by facilitating ‘bidding up’.
- Consumers either underpay or overpay for the real cost of the energy depending on their time of use (TOU).
- Infra-structure is underutilised.
- Increased power losses.

In extreme situations, the wholesale price of electricity can rise to many times its average, as happened in California in 2000, with prices peaking over $1000/MWh (ibid). Whilst this example was caused by a range of issues including a questionable
market design, it is recognised that even modest demand response can both moderate extremes in wholesale prices and avert blackouts when demand cannot be met.

Constraints such as transmission capacity, combined with peak demand can cause localised increases in the market power of generators; this provides increased incentives for operators to manipulate the wholesale energy price by withholding service. Borenstien et al. have demonstrated that market power in electricity systems can vary considerably both spatially and temporally depending on transmission constraints, and that these extremes can be mitigated with demand response (Borenstein, Bushnell et al. 1999).

The domestic consumer is insulated from such price volatility by average pricing\textsuperscript{53}, but pays in the long term. The effect of this lack of demand response is that average prices are higher because all the risk of price volatility is paid for by the consumer. According to Hirst, retail electricity prices reflect two components that should be priced separately. Firstly, the electricity commodity and secondly the ‘insurance premium’ that protects customers from price variation (Hirst 2002). Moreover, whether or not consumers use energy at peak, they pay for it which represents a cross subsidy between consumers with different load profiles.

Conversely, a highly responsive demand side, including micro-generation as per the Gelling definition of DSM, would have manifold benefits. There are a number of practical benefits to a flatter national demand curve including:

- Higher generator load factor.
- A ‘double dividend’ of increasing use of efficient plant and decreased use of inefficient plant.
- Fewer resources are required to support a ‘steady state’ system.
- Inefficiency plant can be retired.
- Investment can be retargeted to DSM activity.
- Least cost planning (for example in IRP) comparisons can be simplified.

\textsuperscript{53} All that is possible with current metering arrangements.
Thus alongside the short term effects of lowering wholesale peak prices and market power, longer term beneficial effects might be seen within the physical system. With the domestic demand responsible for around 43% of peak (Defra 2006), it would appear that there is scope for significant demand response from this sector. The extent of this response depends on the services that can be deferred and consumer willingness to participate. Table 25 attempts to provide a classification of demand response types, the nature of participation and metering requirements.
Table 25 Options for demand response.

<table>
<thead>
<tr>
<th>Demand side activity</th>
<th>Example</th>
<th>Benefit</th>
<th>Metering Requirements</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choosing to avoid peak TOU prices.</td>
<td>Customer chooses to wait before switching on washing machine.</td>
<td>Customer saves money by avoiding peak rate. Smoother demand curve, less carbon emissions.</td>
<td>TOU metering allows different pricing for peaks, creating incentive for load shifting.</td>
<td></td>
</tr>
<tr>
<td>Choosing to respond to critical peak price.</td>
<td>Upon CPP signal customer chooses to switch off or defer washing machine.</td>
<td>Peak price is avoided by customer. System capacity risk premium is reduced if load reduction is predictable and significant.</td>
<td>CPP meter records demand at critical peak. e.g. French Tempo (next day) or Ambient Orb, (time of day)</td>
<td>US Trial revealed participant interest in automation as alternative.</td>
</tr>
<tr>
<td>Semi-automated, response to critical peak, (option must be selected)</td>
<td>Washing machine pauses automatically. (override option not selected)</td>
<td>As above.</td>
<td>CPP meter records demand at critical peak.</td>
<td>Meter needed to account for participation otherwise free rider problem.</td>
</tr>
<tr>
<td>Automatic response to critical peak.</td>
<td>Washing machine pauses automatically. No override.</td>
<td>Average price is reduced. System capacity risk premium is reduced because reduction is predictable.</td>
<td>No meter needed. Because participation is guaranteed.</td>
<td>Lower flat tariff or other incentive needed.</td>
</tr>
<tr>
<td>Appliance responds to grid frequency.</td>
<td>Fridge with 'Dynamic demand' technology.</td>
<td>Grid management costs are reduced, thus lower average prices.</td>
<td>Lowers ancillary service costs. Frequency response is not typically metered in electricity retail.</td>
<td>Unusual in that is does not relate to TOU or CPP. Currently in testing phase.</td>
</tr>
</tbody>
</table>
5.3 Losses: Between generators and the meter

Technical losses\(^{54}\) are caused by impedance in the network, inherent in cables and transformers and result in energy lost as heat.

The national demand curves, shown earlier, reflect the demand seen at the supply side: in other words the sum off all electricity generator output profiles. This is not the same as the demand profile if it were the sum of each consumer's meter reading. If we could compare the load seen at the supply side with the aggregate demand seen at the meter, we would see that the supply side is greater and more peaked due to the physics of electrical losses.

On the transmission network, because of the diversity of loads, the demand curve is relatively smooth, and because the transmission system uses very high voltages, losses are comparatively low at around \(~1.4\%\) of total supply. The opposite is true of distribution networks which lack the high voltages and diversity of the transmission system (Willis 1997). Low voltages result in distribution systems being responsible for a larger proportion of system losses at \(~5.6\%\) of total supply (DTI 2006).

Figure 21 represents a rough estimate of the seasonal and diurnal variance of transmission losses, based on an average of 1.4\%. These data were derived from national grid demand curves as listed\(^{55}\); they assume a single transmission line and all losses to be variable.

\(^{54}\) Non technical losses refer to fraud and accounting errors of un-metered loads.

\(^{55}\) Data is from 2003
In practice losses on any part of the system comprise a fixed and a variable component. Fixed losses account for around $\frac{1}{4}$ to $\frac{1}{3}$ of the total, and are caused by a range of factors, transformer core losses being most significant (Ofgem 2003). Variable losses represent the remaining $\frac{2}{3}$ to $\frac{3}{4}$ and increase in proportion to the square of the load, following the $I^2R$ law (Gonen 1986). This means that at peak, a considerable amount of energy is wasted, in practical terms heating cables and transformers. By avoiding times of peak demand the losses associated with a specific end-use can be reduced. At the lowest voltage levels, the lack of diversity will tend to make the magnitude of losses fluctuate considerably, depending on the coincidence with other loads on the system.

In the current market framework, distribution losses are calculated by taking the difference between the input and output profiles from the distribution network. Each DNO has its own voltage level and time based (half hourly) loss adjustment factors (LAF). The LAF is used to calculate how much extra power the supplier must buy on the wholesale market to compensate for losses (Jamash, Neuhoff et al. 2005).
Distributors include consideration of losses in their investment decisions, where capital investment is considered against operational expenditure (Curcic, Strbac et al. 2001). The responsibility for reducing losses on the distribution network lies with the DNOs (Ofgem 2003), who are rewarded per unit of reduced loss based on historical performance. However the DNOs do not appear to be greatly motivated to reduce losses (Ofgem 2003). The metrics used by Ofgem to measure DNO performance are customer focused and relate to security of supply (Customer Minutes Lost (CML) and Customer Interruptions (CI)) and losses are a lower priority. Because distribution losses vary considerably against time and location, end users are well placed to minimise them, although it is not clear how the appropriate signals would be delivered or how demand side participation could be valued.

Earlier we noted that if losses and generation costs are divided equally amongst all consumer sectors, then domestic electricity is responsible for ~12% of CO₂ emissions. This figure may be an underestimate because the domestic sector operates at low voltage and individual houses have very peaky demand; conversely industrial consumers are often connected at higher voltage levels (SP 2003).

Measures aimed at reducing electricity demand peaks, for example TOU tariffs as described earlier, do not necessarily reduce total energy use, as seen at the meter. They may however reduce the energy delivered to the electricity system through reduction of losses. Moreover, this is likely to be at times when generator plant tends to be less efficient than that used for base-load.

This said, since the actual magnitude of any given loss is specific to each cable and load at any given time, as load diversity decreases losses become less predictable. The subject of losses appears infrequently in the energy policy discourse and when discussed are typically associated with the benefits of reducing distribution system investment:

‘a reduction in electricity losses that occur when a generation plant is situated close to demand sites that translates into lower generation requirements and lower carbon emissions. This can help to avoid the need for investment in
large central energy networks that have their own carbon and environmental footprint; ‘

(Ofgem 2007)

In the above example we see the issues of losses and system capacity investment somewhat conflated, the benefits of decentralised generation in relation to losses might be better described as:

- Reduced **average** demand from transmission network.
- Thus improved average supply side capacity
- Reduced losses when generation is coincidental with high demand.
- Thus further reduced average demand from transmission network.

In summary demand side activities that avoid peak have a two fold benefit. Firstly the load removed from the peak can be considered as ‘load + losses’ and because losses are higher at peak, we are in effect removing a bigger load than its rated wattage. Secondly this occurs at a time when generators will typically be less efficient and thus use more fuel.

At the time of writing the economics of gas versus coal tended to make coal run base load. In the future the ETS may push carbon generation to the margin and in turn increase the benefits of load shaping. Grubb et al. identify such a switch to gas for base load as practical way to reduce carbon emissions (Grubb, Jamasb et al. 2008).
5.4 Accounting for electricity use and losses

All electricity meters in the UK have a unique Meter Point Administration Number (MPAN) and this can be found on all electricity meters and bills issued in the UK. Figure 22 presents a breakdown for interpretation of the 22 digit number.

![Figure 22 Meter point administration number encoding (Energylinx 2008)]

5.4.1 Profile Classes
Because smaller customers do not have half hourly metering, it is not possible to accurately calculate their individual contribution to the diurnal supply costs. Profile classes, of which there are currently eight, provide a proxy for actual customer demand profiles. This means that all customers in a class are billed as if they had the same shaped demand profile but with varying volume. The profile classes have the following interpretation:

- 01 Domestic Unrestricted
- 02 Domestic Economy 7
- 03 Non-Domestic Unrestricted
- 04 Non-Domestic Economy 7
- 05 Non-Domestic Maximum Demand 0-20% Load Factor
- 06 Non-Domestic Maximum Demand 20-30% Load Factor
- 07 Non-Domestic Maximum Demand 30-40% Load Factor
- 08 Non-Domestic Maximum Demand >40% Load Factor
For example profile class 01 refers to all non Economy7 domestic customers. For any given day, the balancing and settling system uses a pre-determined load profile for calculating the costs of these customers.

Figure 23 shows the average demand curves for Profile Class 1 over the ten years to 2007: It demonstrates the wide variation in domestic electricity demand throughout the year.

The Profile Class 01 curves are derived from sub-metering operations performed on behalf of Elexon, the Balancing and Settlement system operators. These profiles are adapted using a multi-linear regression to compensate for demand variance related to, for example, temperature and sunlight56 (Spencer 2005).

56 In practice the current UK system currently uses 15 regression coefficients.
5.4.2 Meter Time Switch Code

The Meter Time Switch Code (MTSC) allows identification of further metering and time switch pattern and capabilities of the metered system (MRASCO 2008). For domestic customers this allows identification of sites with Economy7 or other time switch capabilities and their sub-coding\textsuperscript{57}.

The MTSC does not have any universal interpretation; rather it is interpreted through tables specific to each DNO. Whilst under OFGEMS predecessor OFFER some efforts were made to rationalise this system (MRASCO 2008) but MTSC encodings remain rather arcane and beyond the scope of this thesis.

5.4.3 Loss Line Factors

The Line Loss Factor (LLF) number allows identification of the distribution losses associated to a specific Metering Point. Again the LLF number has no inherent meaning but as with MTSC it is used to index actual values known as Loss Adjustment Factors (LAFs). Like the profile classes, these are not single values but curves that reflect seasonal and diurnal variation. Since losses depend on local network configuration, which changes with network upgrades and load which is variable, specific LAF curves are provided for specific locations and different periods\textsuperscript{58}.

\textsuperscript{57} In one DNO many sub codes may exist to allow staggering of load switching to aid network management.

\textsuperscript{58} These data are available on the Elexon website.
Figure 24 Two example Loss Adjustment Factor curves (LAF) for the author’s home in 2008.

Figure 24 demonstrates two LAF curves for the author’s area in South London (SE24). The modified profile class curve introduced earlier is multiplied by the LAF curve to produce an estimated customer demand curve as seen by the wider system, that is, up to the local Grid Supply Point (GSP) on the transmission network.

The lack of the domestic daytime dip in the LAF curve suggests that these loss values must relate to a number of profile classes\(^{59}\). Because the LAF curve represents a mix of consumer classes it masks the dynamics that might be seen on the low voltage system.

### 5.5 Summary

In this brief review of issues relating the supply of domestic electricity, we have touched upon the physical supply ‘chain’ from the power stations to the domestic electricity meter. Each component in the system has an impact on the carbon intensity of the kWh as ‘read at the meter’. The carbon intensity of electricity supplied to the

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\(^{59}\) Commercial and industrial profiles do not have the domestic morning and evening peak.
grid ‘supply side’ varies considerably, roughly between 0.3 and 0.6 Kg per kWh (Boardman, Darby et al. 2005).

Losses cause an additional energy demand of around 10% compared to what is read at the meter; therefore if we are to reflect carbon intensity accurately losses should be accounted for. However losses are difficult to predict, the further down the supply chain, the less we know about their spatial and temporal magnitude. This said, the laws of physics dictate a relationship between losses and load, and where there is reasonable level of diversity, we can estimate losses with some accuracy. At the ‘street level’ however, with ten’s of houses as opposed to thousands, losses will clearly be more erratic.

In summary, if we compromise on how we account for electricity then there can be wide variation between estimate and reality. While losses account for only around 10% on average, it is likely that in some situations, say peak time on a heavily loaded neighbourhood might be in the region of 20%. The demand response mechanisms described could in theory assist in the reduction of carbon intensity throughout the supply chain, but again, at the low voltage end of the system, local conditions may warrant different demand response strategies, for example ripple control.

The electricity meter technology to a large extent dictates the options for demand response in that it both provides the signals for participation, for example tariff and load level as well as providing the means to account for participation.
6 Metering policy

6.1 The role of metrology in society

*Prima facie* the subject of metrology might be viewed as confined to the science of measurement, indeed the international body responsible for measurement standards, the Bureau International des Poids et Mesures (BIPM), states:

‘Metrology is the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology.’

(BIPM 2004)

Since this definition includes ‘theoretical determinations’, we can consider it to include processes of modelling and well as physical measurement. Following the above definition they add:

‘Measurement science is not, however, purely the preserve of scientists. It is something of vital importance to us all. The intricate but invisible network of services, suppliers and communications upon which we are all dependent rely on metrology for their efficient and reliable operation.’

(ibid)

Measurement technologies are a ubiquitous part of modern life, from the weighing scales in the supermarket, to the diabetic’s insulin monitor, and the speed camera on the roadside. In turn these technologies are supporting social systems of trade, health and law and as such are enmeshed into our society. Legal metrology60 has developed over thousands of years, born of the need for consistency in the measurement of time and physical quantities. The relationship between metrology and state can be said to be symbiotic:

‘The State needed measurements to provide the information necessary to organise, plan, defend and tax with efficiency……… Metrology on the other hand required the mandate of the State to ensure conformity to measurement requirements.’

(Birch 2003)

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60 Measurement systems enforced by the state.
A review for the International Committee of Legal Metrology (CIML) offers a list of some social and economic benefits of legal metrology:

- Support of a civil society
- Technological education
- Reduction of deaths and injuries from accidents.
- Improvement in the natural environment
- Improved health from standardisation of measurement and testing

(ibid)

The benefits of metrology then are for the most part public goods and as such relate to responsibilities of the state. Except for point 5, these benefits can be mapped directly to current energy policy concerns and potential to the potential benefits of smart metering, see table 26.

<table>
<thead>
<tr>
<th>Generalised Benefit</th>
<th>Climate change benefit</th>
<th>Energy security benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support for civil society</td>
<td>Government legitimacy, avoiding free riders, market efficiency.</td>
<td>'Keeping the lights on'.</td>
</tr>
<tr>
<td>Technological education</td>
<td>Improving understanding of energy services and options for efficiency.</td>
<td>Improving understanding of options for system resilience.</td>
</tr>
<tr>
<td>Reduction of deaths and injury</td>
<td>Emission reductions to sustain living environment.</td>
<td>Managing an equitable distribution of energy ('for example fuel poor').</td>
</tr>
<tr>
<td>Improvement for natural environment</td>
<td>Reducing pollution through efficiency.</td>
<td>Fuel efficiency benefits energy security.</td>
</tr>
</tbody>
</table>
6.2 The ‘smart metering’ discourse in the UK

The domestic electricity meter serves a number of roles; it provides an informational interface for the purposes of billing, it physically demarks the boundary of the distribution network and the home, and it can facilitate a range of approaches to DSM, as discussed in the previous chapters.

Established metering and billing arrangements, which treat electrical energy as if it were a uniform commodity, have been criticised for not fostering an understanding of the relative costs of energy services (Devine-Wright 2006). These arrangements, coupled with energy costs being only a small portion of typical household budgets, have resulted in a population which considers little about how it uses electricity or the associated consequences (Darby 2005).

In the early days of electrification, when only lighting services were available, providers simply measured the duration of lighting services, to calculate a ‘bulb hours’ tariff (Wales 2009). As loads rapidly diversified, it became necessary to measure actual power flow, and the Watt hour became the new metric in electricity services. Except for modern pre-payment card meters, and ‘Economy7’ systems, domestic electricity meters have not significantly changed since the invention of the first modern electricity meter, the GE Type I meter in 1903 (ibid).

Since nationalisation, the provision of domestic electricity metering has been the responsibility of the DNO companies, with the meter asset being considered part of the local distribution infra-structure. This changed following the liberalisation of the electricity market, with retail competition being introduced for 1MW+ users in 1990, 100KW+ in 1994, reaching the domestic sector with full competition in 1998. These changes led to a transfer of metering to full competition in three phases, namely:

- Distribution (before March 2005), meter provision was the responsibility of DNOs, with all meter charges passed on to suppliers as part of distribution charges.
• Transitional arrangement (to April 2007), existing and new basic meter ('non-smart') provision continued to be passed on by DNOs to suppliers pending full competition of meter asset provision (MAP) and meter operation (installation, maintenance, repair, removal) (MOp).

• Competitive framework (after April 2007), provision of all new meters became a non-price controlled activity, subject to competition. Under this arrangement the DNOs can only maintain old meter stock, all new work must be conducted through a separate subsidiary.

(Owen and Ward 2006)

These changes form the backdrop of UK legislation which was required, in 2008, to comply with the Energy Service Directive, aimed at stimulating demand side activity:

‘The aim of this Directive is not only to continue to promote the supply side of energy services, but also to create stronger incentives for the demand side.’

(EU 2006)

The directive specifically identifies metering as an important component in facilitating these objectives:

‘Member States shall ensure that, in so far as it is technically possible, financially reasonable and proportionate in relation to the potential energy savings, final customers for electricity, natural gas, district heating and/or cooling and domestic hot water are provided with competitively priced individual meters that accurately reflect the final customer's actual energy consumption and that provide information on actual time of use.’

(ibid)

Advanced metering technologies are being widely deployed throughout Europe (France, Netherlands, Italy and Scandinavia), with metering technology reflecting respective national energy systems and policy objectives. However, the roll-out programmes delivered to date have been conducted by regulated monopolies and as
such unhindered by issues of competition, and diffuse responsibilities, costs and benefits. Thus whilst the UK might, in metering terms, be viewed as a ‘laggard state’ it faces unique challenges with a highly disaggregated energy sector.

Attempting to understand the likely policy outcomes from drivers such as the ESD is difficult in the UK’s liberalised market, since it necessarily involves greater mediation between stakeholders. Each stake-holder’s position is framed by commercial interests and institutional paradigms, and their input to the debate is also affected by their relationships with other stakeholders.

The choice of metering technology will affect both the scope for future domestic demand side participation (DSP), domestic micro-generation and system integration in what has become known as ‘smart grids’.

In terms of issues relating to CO₂ reduction, much of the UK discourse has focussed on the question of to what extent people will change their behaviour in response to improved feedback about their energy consumption using real-time displays and improved billing. Because of the lack of UK studies, in 2007 the UK Government backed trials of ‘smart metering’ which aimed to ascertain the likely consumer response to a number of existing technologies (Ofgem 2007), despite positive evidence from studies overseas.

While metering has been shown to engender behavioural change, as discussed in chapter 4 there are a range of other services that improved metering could facilitate. The types of services that can be facilitated using metering depend on the technology deployed, including the frequency and predictability of communications links and the type, resolution and quantity of data recorded:

- The fundamental service of billing can be enhanced through Automatic Meter Reading (AMR), which removes the need for estimates. This requires the supplier to be able to download a meter reading remotely, for example using a phone system or the internet.
• Automated Meter Management (AMM) allows meters to be configured remotely, for example to adjust tariff periods.

• Time Of Use (TOU) tariffs require a meter to have multiple registers that reflect the consumption for different periods. AMR and TOU metering are already in widespread use in the industrial and commercial sectors and could be adopted in the domestic sector.

• Control of loads can be facilitated through metering, the Economy 7 tariff using radio signals to remote control electrical water and space heating systems being a familiar example in the UK.

• Communication through AMR offers the prospect of other services, for example alerting customers to impending equipment faults, tariff change recommendations, and energy efficiency advice.

• Non-energy related services can also be provided, such as ‘panic buttons’ for the elderly.

Without making assumptions about what a meter is in technical terms we can first consider what objectives it might facilitate. The following checklist enumerates possible emission reductions benefits resulting from an idealised electricity meter:

• Improved ‘energy literacy’ of population
• Less per capita wastage
• Better informed purchasing
• Improved patterns of use
• Improved technical operation of system
• Support for lower carbon generation options
• Improved system efficiency

This generalised list reflects the meter’s possible roles as a social and technical interface, being both a source of information for purposes of social and market
transformation and a platform for further technical developments. Importantly, none of these benefits are delivered by the meter itself; rather the benefits come from the development and response of the wider system.

The UK regulatory changes and the European Directive, and concern about climate change have given rise to a public debate about the benefits of ‘smart meters’. The debate has been framed by the concerns of four main constituencies: consumer and environmental groups (NGOs), Government, the utility companies, and IT providers or ‘technocrats’. The following four sub-sections describe the key issues raised by these groups as the metering debate developed.

6.2.1 Non Government Organisations

Non Government Organisations (NGOs) appeared to be advocates for the idea that informing the consumer is an important activity in the fight against climate change and fuel poverty. This group seemed to concentrate specifically on technology that uses ‘in home displays’ to inform the user on how much energy they have used and are using, as per Darby’s ‘direct feedback’. In August 2005 Energywatch (energywatch 2005), the gas and electricity watchdog, produced a report endorsing smart metering for the domestic sector. This was the first significant report on metering following the change in the regulatory framework. The report cited a range of benefits from smart metering namely:

- Reduced energy bills for the consumer (based on estimates of 3-15% savings);
- Accurate billing, avoiding debt ‘lock-in’ to suppliers;
- Lower carbon emissions;
- Improved energy security;
- Facilitation of micro-generation;
- Improved supplier-customer relationships from accurate billing;
- Opportunity for innovative demand management tariffs from improved understanding of demand patterns.

(energywatch 2005)
Pro-metering sentiments are however often tempered by concern about individual consumers, particularly those vulnerable. For example concerns about the scale of cost passed onto customers, privacy of information and concern that roll-outs\textsuperscript{61} could be used by ‘distraction burglars\textsuperscript{62} were raised by groups such as Age Concern (Jones 2009).

Energywatch’s early contribution to the debate identified the smearing of benefits between the various actors, with the majority of the benefits not necessarily accrued by the suppliers who are now responsible for meter provision:

‘The lack of any requirements for smart meters, or perceived benefits to any single agent in the energy industry, has seen the continuation of the installation of non-smart meters. We therefore recommend requiring that all new and replacement meters are capable of showing time-based consumption in terms of cost and kWhs and of being read remotely.’

(energywatch 2005)

The issue of whether or not government should mandate smart metering became a key thread in the debate, and suppliers later came to adopt this position. Whether or not metering is mandated, the regulatory changes are problematic because consumers can change suppliers every 28 days:

‘Consumer churn raises the fear among suppliers of creating stranded assets. We therefore recommend a review of meter ownership arrangements and the possibility of transferring this to distribution network operators in electricity and transporters in gas, as is the case in many other energy markets worldwide.’

(ibid)

This recommendation however is in direct conflict with the primary legislation of the 1989 Energy Act which assigns responsibility to suppliers. Interrelated to the issue of meter ownership is the question of what has become known as ‘interoperability’:

\textsuperscript{61} ‘Roll-out’ is meter industry jargon for large scale installation programmes.
\textsuperscript{62} For example, a burglar might pose as an engineer using a metering roll-out as a cover story.
Lack of common standards in terms of what such technology should include may have caused uncertainty. We therefore recommend the development of guidance/requirements for minimum standards such as data transfer protocols.\(^{(ibid)}\)

Without common standards in the interface and data types provided by meters, meters would become either proprietary technology, usable by only one supplier, or supplier MOP and MAP services would require multiple systems to access and process meter data.

### 6.2.2 Government and regulator

At the time of the initial Ofgem consultation the Department of Trade and Industry DTI\(^{63}\) was responsible for metering policy. However, in line with the free-market ideology, they assumed a position of observer, deferring to Ofgem, explaining that as industry regulator they were responsible for issues surrounding ‘smart meters’\(^{64}\).

Ofgem initiated a consultation process ‘Domestic Metering Innovation’ in 2006 (Ofgem 2006). Despite its title, Ofgem’s consultation was not concerned with innovation, but instead focussed on discussion of typical\(^{65}\) ‘smart meter’ features (AMR, AMM) and a cost benefit analysis (CBA) of meter deployment.

Ofgem’s position was that suppliers are the ‘customer facing’ part of the industry and as such should be responsible for improving consumer information and billing, in their thinking this included responsibility for all the physical assets of new metering systems (Ofgem 2006).

Ofgem repeatedly stressed the importance of not ‘picking winners’ but they made no distinction between ‘smart meters’ and the underlying standards and infra-structure

\(^{63}\) Later to become the department for Business, Enterprise and Regulatory Reform (BERR).

\(^{64}\) Round table discussion at the first Adam Smith Metering Forum in 2007.

\(^{65}\) In commercially available technology for domestic premises.
that is required to support them. Their expectation was that, under the pressure of ‘market pull’ from consumer interest, the suppliers would collaborate and make progress in these areas.

The initial consultation report claimed that the case for mandating smart metering was marginal, due largely to an estimate of an average demand reduction of 1%. Only absolute reductions in energy consumption by end users were considered, excluding the benefits of time of day pricing, peak reduction, or wider systemic change.

The one percent estimate of potential energy savings was critical in positioning the benefits of domestic smart metering as marginal. However this estimate was the low side of estimates made in a report by consultants Sustainability First:

‘The major long term evidence to date on energy-saving is from a Norwegian study based on ‘informative-billing’ in homes with electric heating – not smart metering – where savings of 4-8% were achieved. A major UK study suggests 3-5% is possible for homes without electric heating. Short-term results with smart prepayment meters in Northern Ireland have shown a 3% energy saving. It therefore seems reasonable to estimate energy savings, on a cautious basis, at around 1-3%. A 3% saving would be £10.50 off an average electricity bill. A 1% saving would equal 8% of the UK’s domestic CO2 target.’

(Owen and Ward 2006)

The limited selection of benefits listed in the Ofgem cost benefit analysis, and a subsequent impact assessment by BERR, resulted in delay of a policy decisions being made, pending further investigation. With the scarcity of empirical evidence the government announced ‘smart metering trails’ to improve their CBA inputs, the focus was on ‘reducing waste’.

‘We are also undertaking trials of smart meters and real time displays which enable people to track their energy use conveniently in their homes. Subject

The lack of a cost argument means that no action is required to comply with the ESD.”
to the results of these trials we intend to work with energy companies to roll these out to households over the next 10 years. In the meantime, real time displays will be provided with any new meters fitted from 2008. Because it will take a number of years before a new meter and display can be rolled out to every household, we have decided that between 2008-2010, real time displays, will be available free of charge to any household that requests one.’

(DTI 2007)

The policy of providing ‘real time displays’, consistent with Centrica’s early position (see below), was strongly resisted by most other parties as being a distraction, and this policy was quietly dropped in early 2008.

Ofgem had resisted calls from both NGOs (see above) and suppliers (see below) for meter services to be run by local monopolies, stressing the potential benefits of competition. The following table is taken from an Ofgem presentation made in 2007, and reflects their pro-market ideology.

Table 27 Ofgem’s comparison of business models for domestic metering (Fletcher 2007).

<table>
<thead>
<tr>
<th>Competitive Model: Supplier Hub</th>
<th>Regulated Model: Distributor Monopoly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price set by tender process</td>
<td>Price set on basis of D67 costs</td>
</tr>
<tr>
<td>Competition on quality of service</td>
<td>Tension between quality of service and the price control</td>
</tr>
<tr>
<td>Suppliers’ total cost to serve influences technology choice</td>
<td>Distributor makes technology choice</td>
</tr>
<tr>
<td>Different technology for different customer categories</td>
<td>Metering offered to suppliers on a one size fits all basis</td>
</tr>
<tr>
<td>Opportunity for supply product differentiation</td>
<td></td>
</tr>
</tbody>
</table>

The list on the left however conflates metering technology and service:

‘Ofgem should specify one metering system that would be made standard across the whole country,’ said a spokesman for Npower. ‘Then energy firms could add plug-ins to allow them to innovate as they see fit.’

(Brown 2006)

67 Taken by the author to mean Distributors costs.
Since 2006 the Energy Retailer Association (ERA) had been working on a smart meter functional specification and which facilitates interoperability between suppliers. Interoperability defines a common feature set for the ‘smart meter’ thus making the meter a generic device. However the definition of the meter does not prescribe service type or quality provided the meter is of appropriate specification. In other words, tariff types and service differentiation are possible with a common meter base. Moreover, commercially available ‘smart meters’ are typically of a high level of functionality in their standard offerings.

Government policy has created a situation where the apparent benefits of metering competition are negated by the very process intended to facilitate a competitive framework. Moreover, conspicuously absent from the Ofgem and other government reports are the manifold costs associated with the competitive framework, explored in more detail in the following section.

Suppliers eventually endorsed the notion of ‘smart metering’ as a key component for ‘market transformation’, but government remained cautious about the potential benefits, not perceiving the current metering arrangements as a significant ‘reverse salient’ to decarbonisation.

6.2.3 Suppliers

Electricity retail is typified as being a low physical asset, high volume, low margin business; third-party MAP and MOp provision will continue to be prevalent unless suppliers see a benefit in the vertical integration of metering. Since it is the suppliers who now dictate metering requirements they can choose to move to new or proprietary MAP and swap out the ex-DNO meters.

However, to be sure of recovering their costs the risk of asset stranding has to be reduced. From a supplier’s perspective, one solution might be to consider the removal of the ‘28 day rule’ that allows customers to change supplier frequently. However Ofgem uses supplier switching figures as evidence to demonstrate that the UK market is healthily competitive.
An alternative solution to the issue of asset stranding, the notion of ‘interoperability’ was developed with the formation of the Ofgem Metering Interoperability Steering Group (MISG), which in turn deferred responsibility to the Energy Retailers Association (ERA). Interoperability of technology is a means by which a customer can change supplier without having to change the meter. This proposed solution does however introduce some apparent conflicts:

- Firstly, the stranding issue is not resolved by interoperability, only the need to change meters is avoided. This is equivalent to solving the stranding issue only if the meters are in effect identical, that is, there being no differentiation in terms of their operation\(^\text{68}\) and the costs being passed on to the new supplier.

- If ‘smart meters’ are not subject to large geographical rolled-outs, then piecemeal replacement is the likely outcome. Given a variety of supplier metering policies, if a customer switches supplier then it is unlikely that the new supplier will offer the same level of service for a given meter (especially if the new supplier’s policy is to continue using default DNO meter stock). Thus the need for assets to remain in situ when a customer switches supplier is a counter-incentive to innovation and product differentiation. This is because suppliers are less likely to develop upstream services for non-standard metering assets since their investment could be lost by a change in their customer base.

Interoperability is however attractive for other reasons, for example it lowers development and information costs for all those involved in communication with meters (suppliers, DNOs, customers) because fewer information technology (IT) systems need to be developed. A corollary of this is that a common metering platform could encourage innovation in energy services, such as data analysis and aggregation services, and including demand side management.

\(^{68}\) Including data to and from supplier and interface to customer.
At the initial Ofgem ‘domestic metering innovation’ conference at Millbank in 2006, suppliers’ presentations focussed mainly on issues relating to customer ‘cost to serve’ and some appeared resistant to the notion that there was a need for change in metering. This group appeared to be concerned that the cost of installing meters is in excess of any savings obtained through reduced cost to serve (manual meter reading is said to be relatively low cost and is unskilled work\textsuperscript{69}). Since the meter is now the supplier’s responsibility, they were also concerned about asset stranding if customers switch supplier. Centrica’s Petter Allison specifically advocated ‘clip-on’ devices as an alternative stating that they provide 90\% of the functionality of smart metering with the benefit of no installation costs and no need for upstream system changes.

Through 2007 and 2008 the suppliers stated positions started to align with the NGO view that meters are a ‘good thing’, some going as far as stating their potential as a ‘revolutionary technology’ (Leiper 2008).

The narrative from the suppliers had changed considerably: The previous position of ‘There is no cost argument for us to role out smart meters.’ had become ‘Meters are clearly of net benefit to society, but there is no cost argument for the supplier’. Thus the supplier’s stated position was that they were unlikely to move to a new metering paradigm without a government mandate.

Another key thread emerged in the same period: that suppliers are not best placed to be responsible for metering as this greatly increases system complexity.

The current market model of ‘full metering competition’ prescribes a system where many commercial actors are engaged in metering services. On gaining a customer, around 25 separate information transactions are required to complete a customer change-over in MAP, MOP and data aggregator activities (Leiper 2008). Since suppliers typically procure metering services from separate companies, each actor managing a particular metering activity for the previous supplier must be informed of

\textsuperscript{69} This was confirmed by ad hoc interviews of meter readers that visited the author’s home (8 at time of writing). They typically stated numbers around 100 reads per day with some claiming 200 and 300 per day where municipal buildings allow easy access to meters. Their rate of read is to an extent governed by the job allocation (on their portable computers). It is perhaps worth considering whether this activity is a natural monopoly: is it worthwhile for multiple agents to be sampling pseudo random addresses where door to door type activity would suffice?
the change and each new actor passed the responsibility. These transaction costs are exacerbated by the need for interlocks to maintain system integrity. If one transaction is delayed it can stall the entire process. The suppliers also claimed that complexity will worsen with smart meters because another layer of complexity will be added to the existing systems. The government’s recalcitrance or lack of understanding on this issue evoked frustration amongst suppliers:

“(The current metering arrangements are) completely barking.”

(Allison 2008)

“We’re blue in the face.”

(Brogden 2008)

“We can’t all be wrong…….THEY need to be prepared to show leadership”

(Sedgwick 2008)

This mismatch between policies intended to promote competition and the resultant manifold complexity is reminiscent of the historic issues of multiple standards in light bulb types, system voltages and frequencies discussed earlier.

As a solution to this issue the ERA proposed that metering be managed by regional franchises as opposed to being put back into the DNOs responsibility as was originally proposed by Energywatch.

With the interoperability specification being defined by the suppliers’ requirements, there is a risk that the concerns of the wider system are not included. Below is an excerpt from the ERA smart meter functional specification:

‘Cost is a consideration – but it is assumed that 4 quadrant will become standard, particularly in light of recent Ofgem statements on microgeneration. Costs are believed to be associated with testing and approval, and processing additional data. If costs prove to be an issue, a 2 quadrant measuring element would be mandatory with a four quadrant element as potential. Meter shall record kWh import and kWh export separately. It is not envisaged that additional information would be required for domestic customers.’

(Harrison and Brogden 2007)
Here we see the ERA proscribing interest in additional data for the domestic consumer. Reactive power flow might have significant costs but metering reactive power could also provide benefit in innovation, for example with non-intrusive load monitoring as will be discussed in the following chapter.

6.2.4 Technocrats

At utility conferences corporate IT system providers gather to promote their respective products and services. The ‘smart metering’ visions of those selling IT services could be described as highly stylised and technology focussed. The future is portrayed as encompassing all the features and services commonly identified by other interest groups, while their focus is largely on the interests of their potential customers, the utilities.

This group stressed the importance of customer segmentation and their differing technology and information needs, consistent with the findings in chapter 4. They also stress the importance of the wider value chain associated with demand side technologies that could be facilitated by smart metering. Companies like Logica, and IBM regularly present their positions at conferences and are clearly keen to be involved in a transformation of energy services.

6.2.5 UK policy position in 2010

The key issues publicly discussed in the metering debate had been limited to largely operational as opposed to technical matters, namely:

- Cost benefit analysis (CBA) - to meter or not to meter
- Roll-out - schedule or piecemeal, geographic
- Business model - supplier, DNO or regional franchise
- Asset stranding - in competitive market
- Interoperability - avoiding the asset stranding issue
These issues are interrelated, for example:

- CBA would not be required if it were not for the need of some form of government intervention. Government intervention would not be necessary if metering competition as defined by the 1989 Energy Act had spawned new approaches.

- Asset stranding would not be an issue if it were not for the fact that responsibility for MAP and MOp were being moved from the DNOs to the suppliers (since customers switch suppliers not DNOs).

In December 2009, after a third government consultation, the recently formed Department for Energy and Climate Change (DECC) announced its position with regards to the future of domestic ‘smart metering’. Contrary to previous more ambivalent positioning, the government now enthusiastically endorsed smart metering:

‘Smart meters will pave the way for a transformation in the way that energy is supplied and consumed, contributing to our goals of energy security and carbon reductions’

(DECC 2009)

In the light of the suppliers’ strong opposition to existing arrangements, the 2009 consultation proposed a new ‘Central Communications Model’ in which a single organisation would be responsible for communications to and from all domestic meters.

While at the time of writing, no details had been established, this approach did appear to resolve the issues associated with the ‘Full Competition’ model. By creating an additional organisation, existing responsibilities do not require a change in primary legislation:
‘This model is expected to minimise the time and risk involved in preparing roll out, in particular since it **avoids changing the disposition of responsibility for metering services.**’

(DECC 2009)

This approach allows continuing competition in the provision of the physical assets, while providing a pathway to fulfil the government’s commitment to a full national roll out by 2020. The government then had accepted the suppliers’ objection to the current arrangements without creating new monopolies and associated risk. However there are clearly risks in having ‘all eggs in one basket’, with large government projects, for example the NHS ‘Spine’ suffering significant overrun:

‘The Spine could have cost the public anywhere between £12bn and £20bn but the government has been hesitant to commit to a full cost review until now. The benefits of the programme have also been difficult to measure, partly because the project has suffered constant set backs which have now pushed it five years behind schedule.’

(Marshall 2009)

While ‘The Spine’ is of an order of magnitude more complex than any system that might be introduced to facilitate advanced metering arrangements, there are nonetheless many issues that would need to be considered. For example, depending on what communication systems are implemented, the system will to some extent rely on the co-operation and effectiveness of third parties. Power line carrier communications would rely on co-operation with DNOs, and GSM communications on the mobile phone system operators.

The 2009 DECC consultation response also departs from previous reports in explicitly endorsing ‘high level functionality’ in smart meters, specifically:

- Automatic meter reading (AMR) with time of use information.
- Automatic meter management (AMM).
- Home area network based on open standards.
- Support for TOU tariffs.
• Load management capabilities to deliver demand side management.
• Remote disconnection capability.
• Exported electricity measurement.
• Capacity to communicate with a measurement device within a micro-generator.

These features are consistent with a vision of a ‘smart grid’ where both the supply side and demand side can be coordinated to provide efficiency and security. The government aims to clarify specific details of how these features will be implemented in 2010, but the breadth of these features may make this problematic. While prescribing a high level of functionality, the government also states that each ‘smart meter’ should be supplied with a ‘standalone display’:

‘In our view the provision of a display is important to securing the consumer benefits of smart metering, delivering real time information to consumers on their energy consumption in a readily accessible form.’

(DECC 2009)

6.3 Summary

In the period following the first Ofgem consultation on smart metering, the energy suppliers’ position of ‘no cost benefit’ appeared recalcitrant and out of kilter with the more positive position of other actors. However as the debate developed, the suppliers became more organised and presented a coherent explanation of why the current regulatory framework was problematic. At the same time the government’s position was more ambiguous, whilst they appeared to want the suppliers to ‘get on with it’ without a mandate they also developed cost benefit analyses which presented the benefits of smart metering as marginal.

The notion of reducing waste has historical precedent and therefore would be expected to be part of the debate. While the range of 1 – 3% in savings was repeatedly discussed, the manifold benefits of demand response were barely mentioned and not quantified. This might in part be due to a conflation of bulk energy use and total
carbon emissions, or the tactics of the suppliers. The absence of significant input from the suppliers on this subject suggests that they are, either not especially interested in demand response for the domestic sector, or else their opinions are commercially sensitive, or they do not see it as a profitable exercise. It is not clear that new TOU or CPP tariffs would be offered by suppliers, given the potential downside to the suppliers of reducing peak demand\textsuperscript{70}.

However load shaping, as discussed in the previous chapter appears to have potentially more scope for carbon reductions than the Ofgem estimates for reducing waste. For example there may be little cost to shifting clothes washing loads to an off peak period provided the same number of washes are completed\textsuperscript{71}. This could have a significant effect on carbon emissions since a low carbon period might result in associated emissions in the region of 0.3-0.4 compared to 0.5-0.6 kg of carbon per kWh.

The Energy Services Directive does state that metering is required only where proportional to benefits and perhaps the marginal CBA was divisive in that it provided government with a holding position while policy was developed. The perception that smart metering could be of only marginal value is in part the result of the institutional practice of cost benefit analysis, which contain a necessarily limited set of variables. For example the Ofgem review in 2006 gave no valuation to benefits of dynamic tariffs and damping of generators market power, as identified in the literature.

The ideology and practice of cost benefit analysis runs as a thread through contemporary UK policy making and has been an important element in the metering policy debate. As with the discussion earlier with regards to the ‘rational choice model’ CBA has come under widespread criticism from those outside the economic-technology centric policy circles. The focus on CBA frames the debate in the economic-technical domain excluding issues relating to socio-technical evolution:

‘One of the reasons why rational choice theory may seem familiar is that it closely resembles and indeed draws heavily on the intellectual underpinnings\textsuperscript{70} Scarcity of supply pushes up the whole sale price benefitting generators.\textsuperscript{71} Some wash schedules may be a routine habit, some more random.
of classical economics. Cost-benefit analysis, for example, is nothing more than a highly quantitative form of rational choice model. As we shall see in the following sections, economics certainly does not have the monopoly on rational choice.’

(Jackson 2005)

However it is also clear that the CBA has appeal:

‘Why has the Department of the Environment [in England] not only resuscitated [cost-benefit analysis] as a method for project assessment but promoted it to a central role in the formulation of environmental policy? .... One reason.... The rewards for believing are great. Believers are offered a Solomon Machine -- a machine that embodies in quantified form the principles of profit maximization, and distributive justice, a machine into which can be fed accurately measured valuations of all the relevant facts, and out of which will flow wealth and even-handed justice for all. For a judge whose working life involves balancing probabilities and weighing up incommensurables, it must be tempting. For civil servants and government ministers, faced with decisions about environmental problems of enormous scale and complexity, and who are unfamiliar with the method's dubious past, its charms must be equally difficult to resist.’

(Adams 1993)

The issue of metering, with its interstitial complexity, distributed and uncertain benefits, and potential for innovation appears a poor candidate for CBA. However, if CBA is a necessity, then a more complex set of inputs, specifically related to benefits seems appropriate. While an exhaustive list is not possible here, we might expect a CBA to include some of the benefits identified in previous chapters:

- Improved energy security through both reduced fuel use and lower peak demand.
- Improved system efficiency.
- Reducing risk of generators gaining market power, lowering average prices.
- Facilitation of increased adoption of micro-generation.
• The potential benefits for energy advice in the absence of sub metering.
• Cultural changes in relationship between the consumer and the energy system.
• Value of data to research community.
• Broader networks effect gained from cumulative experience.

Metering practitioners stress that metering alone will not cause change (Pocock 2007), thus in a sense it is not the meter but the wider system, including metering that requires evaluation. Metering technology also determines the future prospects for the accuracy and resolution of demand data available for research, thus limiting the activities of government, research establishments and regulators.

In an apparent change of emphasis DECC appeared in late 2009 to have distanced itself from a reliance on CBA, and instead embraced a vision of radical transformation of domestic energy services (DECC 2009).

What technology is eventually delivered and issues such as what actors have access to what data, will to an extent define the future of the energy system, in terms of technology, services and responsibilities, in what Guy and Marvin describe as Technical Development Pathways (Guy and Marvin 1995). The governments stated ‘high functionality’ requirements for the domestic meter appear progressive, and could facilitate a broad range of services. The competitive model originally conceived in part to foster innovation, would have been problematic, for reasons over and above those already stated. More specifically, the best available technology does not always prevail in a competitive market, as discussed in relation to ‘lock-in’ (Arthur 1989; Unruh 2000). If technology had been rolled out earlier by the suppliers, it would have likely not had such a rich feature set as that proposed by DECC. This technology would have gained momentum in that upstream services would be developed, further promoting the established approach with ‘path dependence’ and ‘lock-in’.

DECC now appear to recognise the importance of including other actors in the specification process and by not relying on competition, lock-in is mitigated. However

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72 Ashley Pocock was head of metering activities in EdF UK at the time of writing.
the prescribing of a ‘standalone display’ does pose some risks. As discussed earlier the process of engendering behavioural change is difficult and nuanced.

Of key importance is that communications methods are tailored to recipient and not ‘generic’. It is not clear that everyone would want or could use a ‘standalone display’ but if mandated then the devices would either need variants or software configurability to suit their audience. As discussed earlier it is not clear what metrics are best suited to what actors and there appears to be a great deal of scope for innovation in the way that energy systems interact with the consumer. Given the above, while lock-in may be mitigated with regards to the smart meter itself, there is risk that visual displays, by being prescribed might impinge on future developments.
7 Measurement and modelling in residential energy demand research

7.1 Research technology

The previous chapter started by identifying the importance of metrology in society including ‘technological education’ (Birch 2003). Metrology can be said to include modelling since it includes ‘both experimental and theoretical determinations’ (BIPM 2004). In another study of the significance and effects of instrumentation and metrology Joerges and Shinn focus on metrology used in research, and propose ‘research technology’ as a subject in its own right:

‘…,while research-technology may eventually increase in size and scope, this does not indicate it is a new form of science. Instead we consider research-technology as a new perspective, an alternative way of looking at instrumentation for social studies of science and technology. Since it is very much a phenomenon “in-between” and often relatively invisible to outside observers, it is not surprising that it has gone largely unnoticed by students of science and technology.’

(Joerges and Shinn 2001)

They go on to argue that the real significance of research technology lies in the trans-community positioning which gives rise to ‘openness or ‘genericity’ of their devices and ‘standardised languages’ by which communities can interact and develop. The benefits of standardisation then, in respect to metrology, extend beyond those of simple interoperability:

‘We can now advance a stronger thesis, namely, that one impact of generic instrumentation is increased social and intellectual cohesion, which runs counter to the on-going differentiation and fragmentation of science and society…..’

(Joerges and Shinn 2001)
These benefits are in a sense the antithesis of ‘lock-in’ network effects introduced earlier. Moreover key to these benefits is the process of what, in innovation studies, is called ‘learning by doing’ (Foxon 2003):

‘….Belief rooted in local experience and testing gradually gains objectivity. Practices are independently repeated and are multiplied in numerous environments. This is not the objectivity born of pure reason or the 
experimentum crucis\textsuperscript{73}. Objectivization is instead built up through collective practice which is structured around effect-producing material and procedures. Here, objectivization is practical and cumulative.’

(Joerges and Shinn 2001)

Projecting these concepts into the arena of energy policy suggests that metrology, that is, including measurement and modelling, provide a framework for collective objectivity, as well as the practical means and language for experimentation. This is important since it suggest that metrology is not a passive constituent of the energy policy debate. On the contrary, the choices made with regards to metrology frame the understanding of both researchers and policy makers and the potential for positive ‘network effects’.

7.2 Approaches to modelling domestic electricity demand

The preceding chapters have outlined a number of aspects of the contemporary UK electricity system. Physical aspects have been described in terms of the supply and demand side as well as the ‘in between’ issues of losses and metering. The role of individuals in demand side management programmes has been discussed, including the complexities of human behaviour. The role of institutions has been discussed in both historic terms and with reference to current policy developments.

This complex system relies on a range of approaches to the 3Ms, with methods tailored to suit different objectives, some of which have already been introduced.

\textsuperscript{73} An experiment capable of determining whether or not a particular hypothesis or theory is correct.
For example, the existing domestic metering arrangements and the profile classes provide a simplified model of the consumer, and these are used as a proxy for actual measurements. This chapter is concerned with the research and development of technical models that assist in the evaluation of the system’s behaviour and the effects of interventions.

At the macro level, long run energy demand forecasting, whilst being notoriously difficult (Smil 2003), is an important, ongoing activity of government and the energy industries. In the UK, historic electricity demand data and future projections can be found in the Digest of UK Energy Statistics (BERR 2009) and National Grid’s seven year statement respectively (nationalgrid 2006). With the UK now dependent on energy imports and vulnerable to global price fluctuations, the subject of demand forecasting appears regularly in the popular press. In the UK a key determinant of energy demand is temperature: a cold winter increases demand for fuel, pushes up prices, depletes reserves, and increases the risk of blackouts.

Long term forecasting is necessary to determine future generation capacity and network capacity requirements. The systems operator also requires estimates for day to day, hour to hour and even minute by minute fluctuations in demand. The UK systems operator uses proprietary models, which rely largely on historic data, modified to compensate for variables such as weather conditions (Taylor and Buizza 2000) and national media events.\textsuperscript{74}

For the purposes of managing supply infrastructure, the National Grid Company and distribution companies also use ‘load flow’ models to analyse network behaviour (Willis 1997). Such models can be used to identify possible system capacity bottlenecks and to evaluate network configurations in terms of capital and operational expenditure.

The following sections examine approaches to modelling that focus on attempts to understand residential energy demand and synthesise electricity demand profiles.

\textsuperscript{74} Media events are important because they have a tendency to synchronise demand, with for example many people putting the kettle on during a break in a popular television programme.
7.2.1 Econometric models

Within the context of residential DSM and ‘Market Transformation’, approaches to modelling have tended to focus on calculating aggregate national demand in GWh. In their simplest form these models use population survey data, appliance ownership data and usage statistics to determine national trends and options for intervention (IEA 1997; Stoecklein, Pollard et al. 1997; Larsen and Nesbakken 2004; MTP 2008).

This econometric approach to modelling has been extended in attempts to further understand the determinants of domestic energy use demand, such as housing type, family size, age group and income (Stoecklein, Pollard et al. 1997). End use studies collect ‘micro-evidence’ from surveys and models are elaborated in the search for the determining factors (Raaij and Verhallen 1982; Leth-Petersen 2001; Larsen, Nybroe et al. 2003; Larsen and Nesbakken 2004).

Significant determinants of energy use are said to include:

- Energy purchase, energy use and maintenance behaviour
- Home characteristics
- Energy related attitudes
- Lifestyle
- Socio-demographics
- Information availability

Weather prediction and housing stock data can be used effectively for predicting heating demand and shed light on options for thermal efficiency, but electricity use with its numerous applications is more difficult to predict. Unlike space heating, electricity demand has been shown to vary considerably within groups of similar housing, suggesting other determining factors such as occupancy and appliance types (Firth, Lomas et al. 2007).

Besides forecasting and targeting interventions, the statistical outputs from such models can also provide insight into the problematic aspects of delivering energy efficiency, as introduced earlier. For example, comparing the variance of heating
energy used in a particular building type might provide estimates of the potential for ‘take back’.

Despite being a common approach to modelling in academic analysis of energy policy, econometric models are commonly criticised for being too abstract, simplistic and unrealistic with, for example, the notion of the ‘rational consumer’ as critiqued earlier. The tradition has however continually adapted to criticism, by for example, models including previously exogenous variables such as ‘bounded rationality’ (Weber 1999).

7.2.2 Engineering models

Where econometric models produce estimates of aggregated demand for a community based on a number of variables and profiles, bottom up models aspire to synthesise the consumption of individual homes and aggregate these to produce a community’s profile. Engineering models tend to be applied to the synthesis of diurnal load profiles and the analysis of load shaping measures.

Early examples of modelling domestic demand focussed on specific appliances and their aggregate demand. For example, within the context of US load management culture, the Carolina utility developed a model for analysing the benefits of scheduling water heaters to improve the demand profile in Carolina using 15 minute resolution (Lee and Wilkins 1983). In this study, only the water heater load pattern was calculated, and this was then used to modify known load profiles.

Such studies have identified the importance of considering the ‘payback patterns’ of demand side management, that is when appliances recoup energy lost during load deferral. This is typically an issue for any heating or cooling process that is interrupted; but the specific ‘payback’ will depend on the specifics of application and is not simply dependent on the period of load interruption (ibid).

More ‘holistic’ models have subsequently been developed; the ‘ARGOS’ model (Capasso, W.Grattieri et al. 1994) represents perhaps the most complex example to
ARGOS attempts to model the behaviour of ‘household members’ who activate appliances based on statistical functions of:

- Occupancy
- Home activities (housework, personal hygiene, cooking or leisure)
- Appliance usage
- Proclivity for activity
- Human resources
- Appliance ownership

The outputs from the behavioural model result in activation of appliances, which again are modelled based on a number of parameters.

- Mode of operation
- Cycle or activation time
- Power demand
- Average annual consumption
- Technological penetration
- Household demand limit (pertinent to Italy which like France has peak demand contracts)
- Technology penetrations

Using the Monte Carlo method a population is created that ‘simulate(s) random differences from the typical average daily behaviour assigned’. Each household in the population is individually synthesised and household demand aggregated to produce a one day, **hour resolution** demand curve for a given population.

A number of variants of this type of approach have been developed. For example a ‘structural model’ (Michalik, Khan et al. 1997; Michalik, Khan et al. 1997) uses surveys to provide input data, using stochastic approaches, in their language ‘fuzzy filters’, to mimic the variance in human behaviour. Again individual house profiles are summed to produce a community profile.
Bottom up models can include ‘physical modelling’ of variables that affect energy demand. This is most suited to heat demand, where the thermal physics of a house are modelled as a ‘system within a system’. In this way, given weather information, property characteristics (such as thermal capacity and loss coefficients), and target temperatures, accurate heating demand profiles can be calculated for individual homes (Pearce, Zahawi et al. 2001) or larger communities (Yao and Steemers 2005).

Whilst econometric and bottom up models are considered distinct approaches, they share a need for demographic and other survey data to tailor their output to real world scenarios. For example, whilst the average energy consumption of a given appliance type and ownership can be estimated relatively accurately, if and when an appliance is used is less certain (Wood and Newborough 2003).

Some attempts have been made to use UK population survey data to model occupant activity; more specifically the UK Time Use Survey (TUS) conducted by the Office for National Statistics (ONS). Richardson et al. use the TUS to model household occupancy, deriving statistical likelihoods of changes in occupant activity using a ‘Markov chain’: changes in activity invoke a change in light demand based on a predetermined matrix of light fittings (Richardson, Thompson et al. 2007). Lampaditou and Leach use the specific activity data in the TUS to select the activation of different load values mimicking variations in appliance, producing load curves for large populations (Lampaditou and Leach 2005). Using low level activity data to activate model loads, it produced low time resolution data for larger populations, based on estimated average demand for appliances.

7.2.3 Data requirements

Any model is reliant on input data, and input data is in part determined by measurement techniques. The accuracy of survey data and electrical measurements become increasingly important as the population size of a model is reduced. This is because the benefits of diversity ‘smoothing effects’ are not present, meaning large sample profile data is not sufficient. Conversely, given that there is increasing uncertainty as modelling resolution increases, modelling becomes increasingly
complex and assumptions have to be made. This tension between complexity and computability has resulted in a range of documented approaches to domestic demand modelling, each approach adopting different assumptions and modelling resolutions.

Computer based, bottom up modelling literature emerged in the 1980s (Capasso, W. Grattieri et al. 1994) and whilst available computational power has increased considerably, it still presents a limitation of the size, complexity, and execution times of models; thus assumptions need to be made. This is also true of data acquisition as resolution increases. Surveys are time consuming and electrical instrumentation is expensive and intrusive (Stoecklein, Pollard et al. 1997), thus there are practical limits to the data available for modelling activities.

This can be mitigated to some extent by using hierarchical sampling; the New Zealand HEEP project collected sample data from neighbourhoods, homes, and appliances (Camilleri, Issacs et al. 2000). The monitoring of individual appliances within a number of homes is aimed at better understanding what the demand profile comprises (IEA 1997). Such programmes are relatively expensive with the need for numerous ‘sub meters’ and computer equipment and therefore it is difficult to obtain statistically significant results. However even modest samples do tend to demonstrate the wide variety in magnitude and composition of domestic demand (Lebot, Lenci et al. 1995; Lebot, Lopes et al. 1997; Firth, Lomas et al. 2007).

This approach can also provide useful evidence of how different load types contribute to peak demand (peak responsibility factors) (Firth, Lomas et al. 2007), with for example cold appliances using more electricity near peak time due to loading and door opening near meal times (Lebot, Lopes et al. 1997).

Obtaining data at the appliance level can also reveal the unexpected:

‘Interestingly, there is no correlation between the age of the clothes washer and its energy consumption, which suggests that the efficiency of these appliances has not significantly improved over the last fifteen years, which is contrary to manufacturers claims. However, efficient new technology stimulated by the new European labelling directive should transform the
average efficiency of the market such that in the future an age/efficiency relationship will be observable.’

(Lebot, Lopes et al. 1997)

The prohibitive cost of large sub-metering projects has led to investigation of alternative methods for the capture of appliance usage data. Since the mid 1980s various techniques have been developed to allow identification of appliances activity by analysing changes in the load characteristics of a home. This approach is now commonly known as ‘Non-intrusive load monitoring’, a variation on ‘Non-intrusive Appliance Loan Monitoring’ originally coined by George Hart of MIT (Hart 1984).

All appliances present a particular load to the system, and vary in terms of active power (Watts) and reactive power (VARs), as well as harmonics in the current flow, and these variations can be used as cues to determine what appliances are active.

One approach is to use ‘impulse analysis’, analyzing the nature of any step change in the load in terms of active and reactive power. One recent study using this approach claims an identification success rate of 80-90% of appliances, although the range of appliances was limited (Deschizeau, Bertrand et al. 2000). However this approach requires on site monitoring or high resolution metering, since any transient data is lost with most metering systems, for example half hourly.

An alternative approach is to post process metered data and pattern match profiles against a database of appliance characteristics. Prudenzi uses such an approach with neural network processing to identify matches, reporting successful identification in 90% of cases (Prudenzi 2002).

Further cues as to what appliances are activated can be gleaned from analysis of the harmonics in the current flow.

7.2.4 Limitations of existing bottom up modelling approaches

While modelling can be used to forecast energy demand and to experiment with long term demographic and technology scenarios, other approaches focus on analysing
short term activity such as load shaping. Whilst there is a reasonable body of literature on the theoretical benefits of load shaping, as introduced earlier, attempts to model load shaping using a ‘bottom up’ approach are more scarce.

Models that use large populations and average demand profiles clearly afford direction to policy makers, but these methods break down when applied to smaller populations and higher time resolutions because of the loss of benefits of diversity.

7.2.4.1 Technical aspects

Despite the term ‘bottom up’ because of the limitations of complexity, data acquisition and computation, engineering models have tended to stop short of including short term appliance behaviour and local network effects. Spatial effects on the network are also often ignored, with the demand modelled as if it were independent of the network:

‘In most previous works concerning the effects of load management, an assumption has been made that any change in demand at the appliance level will directly affect system demand. For example reduction of the demand of a water heater by one kW is assumed to yield a one kW reduction in the system at that time. In the actual operating environment, losses occur on various segments of the power system, and hence, strictly speaking, these foregoings are not valid……

……It should be noted that using diversity and peak responsibility factors for this purpose is not allowed since all of the time series load information is lost in the analysis.’

(Lee and Wilkins 1983)

Modelling of domestic load profiles has used typically used sample periods in the order of 15/30/60 minutes (Willis 1997), and such time resolutions are effective for supply side planning, but may not be adequate for an analysis of the micro-economics and environmental costs of individual homes. For example, losses incurred by a single end-use are dependent on other end-use activity on the distribution network. Using a
sample frequency that is in the order of seconds rather than minutes would allow the costs of coincident *end-use* activity to be more accurately accounted for. Also, if an accurate analysis of the benefits of micro-generation is to be modelled, then it is important that the correlation between generation and demand is properly understood.

Empirical work has demonstrated that domestic load profiles can vary rapidly, with many load events lasting seconds rather than minutes (Ortmeyer and Krishnamurthi 2002), suggesting a need for high time resolution if modelling local network effects.

Other work has analysed the effects of fluctuating demand on the benefits of micro-generation, finding that time resolution in modelling has a significant effect on imported energy calculations. Since lower time resolutions in effect make demand peaks shorter and wider, they tend to also correlate more closely to micro-generation output and underestimate energy import (Wright and Firth 2006).

Another complexity in domestic energy systems that is often omitted from more complex models is the interaction of components within the home. The most obvious example of this is the passive heat generated by appliances which can affect heating and cooling requirements of a building. All appliances create some heat, but some also respond to environmental conditions. Cold appliances are affected by room temperature, whilst also affecting room temperature. Washing machines and dishwashers also respond to water temperature whilst affecting room temperature.

### 7.2.4.2 Behavioural aspects

Modelling large populations does not require consideration of the actions of individuals, since these are replaced by average load profile classes.

If we wish to ‘zoom in’ on the network and analyse localised interventions in a neighbourhood or household, then we need some sense of what individual household occupants are doing.
Bottom up models tend to use stochastic approaches to determine the likelihood of any given appliance being activated, see for example Capasso et al. or Guttromson et al. but these typically treat events as unrelated. (Capasso, W.Grattieri et al. 1994; Guttromson, Chassin et al. 2003) In reality, events are not necessarily independent. If we consider a meal time, then it is likely to be preceded by cooking and followed by dishwashing. Thus if a purely stochastic approach is taken, activity may appear unrealistically diverse, when in fact many people are involved in similar activities.

This problem is mitigated by the use of detailed survey data for example the ONS TUS since the data represents a ‘narrative’ of the activities of the home occupants. This said, within a given activity there may be a great deal of variance as to how it is actually conducted. For example, specific use of appliances may vary a great deal especially in more complex activities like cooking.

Whilst survey data provides us with a chronology of activities it falls short of defining what and when appliances are activated. As described earlier, much of these specifics will be encoded in personal habits and social norms.
8 Energy management in the commercial and industrial sectors

Considered in its fullest sense the electricity system might seem overwhelmingly complicated, comprising multiple, interacting evolutionary paths and influenced by the vagaries of human behaviour, social norms and technical developments.

However there is a well developed culture of energy management in the commercial and industrial sectors, whose systems are no less complex than in the domestic setting. Because no two businesses are identical, energy conservation methodologies provide practical, generalised solutions that can be mapped onto any system requiring energy management.

Text books on energy conservation and energy management have historically been focussed on industrial and commercial (C&I) sectors (for example Jacques, Lesourd et al. 1988; O'Callaghan 1992) and advise on the technicalities and economics of reducing energy costs. Such texts are aimed at energy managers and engineers, who are typically employed in companies where it is justified by energy costs. Managers can also call upon a wide range of expertise from professional consultants affiliated with organisations such as ESTA (The Energy Services Trade Association).

At the core of ‘energy conservation’ lies the requirement for ‘energy accounting’ to identify patterns of energy use and monitor the effect of changes to equipment or processes:

‘Firstly, no useful energy accounting systems will have been generated unless, as noted by Consonni and Lesourd (1986), a clear division into subsystems of the plant, or firm, is achieved. This means having a clear vision of the various operations, shops, and energy cost centres of the firm’s production processes. This means that the energy manager, or whoever is responsible for the operations of the energy accounting system, be familiar technically with
the process and the production system at whatever level he or she is supposed

to act (production unit, firm, industrial group) ‘

(Jacques, Lesourd et al. 1988)

This division of subsystems is perhaps a straightforward task in the domestic setting,
the categories introduced in chapter 3 being universal and ownership statistics being

captured in national surveys. However the actual energy use within these categories

can vary considerably depending on habits and other lifestyle factors. Thus there is a

need to identify the costs associated with specific activity:

‘This condition being fulfilled, technical monitoring and measurement

problems must be solved…..The computer is by no means indispensable in the

operation of the system, whereas the metering equipment and the

involvement of personnel are essential ‘

(ibid)

In the domestic setting however, the cost of metering individual appliances or even
circuits may prove prohibitive compared to the amount of energy saving available.
The process of monitoring an appliance may only be of transient interest, for example
during the process of an energy audit, in identifying a merit order of measures that can
be performed. Moreover monitoring appliances is not simply a case of plugging in a
monitor device since some appliance types, for example boilers, lighting and cookers
do not have a plug and socket.

Given the higher relative costs of sub metering in the domestic sector, non intrusive
load monitoring might provide a means to assist in the management of domestic
energy use. Whilst understanding subsystems and measurement are key, C&I energy
conservation methodologies also recognise the importance of human actors as part of
a ‘system’:

‘We must always be alert to the fact we are conserving energy within a

complicated system of human and machine activities. ‘

(S.Faukes, J.Gazerian et al. 2001)
They also reflect the findings introduced earlier, that the means and content of communication are fundamental to the process of participation:

‘Obviously, nobody would accept and adhere to a project unless he has fully understood it. **Only then can he identify his own part and participation in the actions to be conducted.** Furthermore, he will keep his motivations alive and carry on inasmuch as tangible results can be seen, and providing he does not form the impression of being cheated he should feel that he deserves some personal enhancement from the participation. For all the above reasons, **all information must be true, unambiguous and credible…..**’

(ibid)

And that multiple means of communication are available to the ‘energy manager’:

‘Numerous means are available for companies to promote and develop the circulation of information: billboards, internal memos, newsletters, answerphone, video tapes, computer networks.’

(S.Faukes, J.Gazerian et al. 2001)

Thus we see clear similarities between the culture of C&I energy conservation and aspirations for the domestic sector. However, the similarities are less clear when we consider the technical measures used in achieving the goal of energy conservation. The text book ‘Energy Management’ (O’Callaghan 1992) offers a checklist for practitioners, with a subsection devoted to electricity. Table 28 reproduces this sublist and relates the issues to the domestic sector:

**Table 28 A check list of electricity related interventions for the C&I sectors, after O’Callaghan.**

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Domestic analogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Examine tariff structure</td>
<td>Benefits of TOU tariffs.</td>
</tr>
<tr>
<td>2. Meter Electricity use for all sectors</td>
<td>Problematic because of smaller energy budget, but could be mitigated with non intrusive monitoring.</td>
</tr>
<tr>
<td>3. Select optimal tariff</td>
<td>As per 1</td>
</tr>
<tr>
<td>4. Attempt to balance load factors</td>
<td>Lowering peak demand through load shaping.</td>
</tr>
<tr>
<td>5. Identify equipment contributing to peak demand</td>
<td>Benefits of TOU tariffs.</td>
</tr>
<tr>
<td>6. Check and correct power factors</td>
<td>Literature is scarce on this subject in relation to the domestic sector.</td>
</tr>
</tbody>
</table>
7. Peak lop | Reducing system costs and energy bill requires TOU metering.
---|---
8. Stagger start up times | As above.
9. Reschedule peak activities | As above.
10. Convert to thermal energy at off peak times and introduce thermal storage | This is in effect what the Economy7 system does for space and water heating.
11. Consider the use of generators to peak lop. | This would be a natural function of domestic CHP where winter heat demand correlates to electricity demand.
12. Try to use night rate electricity (for charging batteries of electric vehicles) | A similar mechanism might become necessary in the domestic sector in electric vehicles become commonplace.
13. Introduce compressed air storage; to lop peak; to use off-peak electricity | Whilst compressed air storage is not seen in the domestic sector this does highlight the potential benefits of storage.
14. Select electrical motors so that they run at near full load | This is probably only an issue with refrigeration as described earlier or perhaps washing machines during load agitation.
15. Maximise power factors – introduce capacitors. | As per 6
16. Switch off plant and lighting when not required | This clearly mirrors the ‘waste’ narrative in the domestic sector debate but interestingly comes lower in this list, below load shaping activity.
17. Pay attention to lighting | As above, and the substitution of technology.
18. Consider the use of a total energy system | This refers to combined heat and power (CHP) or combined heat power and cooling systems (tri-gen). Whilst common place in C&I is not typically applied in the residential sector.
19. Invest in an energy management control system. | The closest analogy to these system in the domestic setting are home automation systems but these tend to be focussed on lifestyle benefits as opposed to energy saving (Hatley, Meador et al. 2005).

Following this checklist O’Callaghan adds the following footnote:

‘**Electricity should only be used as a last resort.** This statement arises from the fact that, for every kWh of electricity consumed, 3 to 4kWh of fossil fuel is consumed at the power station.’

This statement seems more concerned with environmental issues as opposed to optimising industrial and commercial energy systems, but it is consistent with the issues of carbon intensity versus energy read at the meter as introduced earlier. However, relating this to the brief review of washing machines technology, the loss of hot water feeds does appear to be a reverse salient in the wider system.
9 Discussion

9.1 Introduction

The previous chapters have examined the UK’s electrical system from a number of perspectives. A historical overview identified some of the complex influences on system development. Large Technical Systems such as the UK electricity system are not built to a plan; they are the result of a stream of innovations and decision-making processes, involving the state, private sector, NGOs and consumers, who often have conflicting objectives. In turn these decision making processes are influenced by historical approaches, ideology and empirical evidence.

The UK’s electricity system was developed from localised systems that served local needs. The move to centralisation, driven by historic social and economic objectives, has introduced significant reverse salients in terms of environmental outcomes. The policy response to climate change has centred on the decarbonisation of electricity supply, largely through the promotion of wind power, and with a renaissance in nuclear power likely to follow: these approaches are consistent with the dominant ‘supply paradigm’. A less energetically pursued demand side policy has tended to focus on objectives of reducing ‘site energy’ measurements, be it kWh or MTOE and corresponding static-passive interventions. These approaches are consistent with notions of the consumer as disinterested and ‘information deficit’, again with carbon emissions reductions being the responsibility of the suppliers.

While issues relating to space heating have received the most attention, typically being the largest part of the domestic energy bill, electricity use and its externalities have received less attention. Despite the rhetorical dominance of markets, policies circa 2010 intended to manage domestic electricity demand are based on a mix of ideological approaches: the European appliance labelling scheme is a measure intended to promote the development of more efficient appliances through ‘market transformation’ driven by consumer choice; the more recent ECC and now CERT schemes are variants of more traditional IRP where measures are prescribed from ‘above’; regulation has recently emerged as the primary means to change the
domestic lighting market, this representing a full circle from pro-market Victorian era legislation where suppliers were prohibited from prescribing lighting technologies.

The remainder of this chapter argues that a significant reshaping of domestic energy culture will require a change of emphasis with regard to roles and responsibilities of the demand side, coupled with efforts to improve the evidence base for demand side interventions. While the privatisation of the electricity system and the climate change agenda have significantly changed the relationship between the state, consumer, and system operators, the systems of metrology used to manage the system and the research technologies which assist our understanding have developed more slowly.

9.2 The 3Ms and electricity use in the home today

Besides the prohibition of less efficient appliances, the appliance labelling scheme and CERT are the two main policies pertaining to the domestic demand side. The appliance labelling scheme has been identified as problematic in that it masks carbon emissions and has not delivered sustained ‘market transformation’. Some aspects of the labelling scheme, for example the lack of open-ended efficiency ratings, may be the result of the private sector out-negotiating government, or simply by a lack of foresight. Whatever the cause, the absence of sustained ‘market transformation’ has been exposed by subsequent policy, most notably in the prohibition of less efficient models, in particular lighting. The labelling scheme is now embedded in the practices of appliance manufactures and retailers, and the government CERT scheme; as well as being familiar to the general public. These interdependencies represent causes of lock-in, whereby an approach to the 3Ms has become enmeshed in legislation and institutional systems. The labelling scheme then will exhibit inertia to change, and induce inertia in constituents of the wider system to which it is connected.

The inadequacies of the scheme may also affect policy maker’s perceptions about the consumer. The label is discussed as being primarily a means of encouraging sales of energy efficient appliances. However, in some appliance classes nearly all available products are A rated: a corollary of this is that there is both little choice for the consumer and in turn little evidence about consumers’ attitudes and sensitivity to
energy efficiency. The CERT scheme has also been identified as problematic from a number of perspectives; the utilities often use generic as opposed to targeted measures, estimates of benefits are based on ex-ante calculations, measures are not audited, and negative customer perceptions of the suppliers affect trust. The operational response of the suppliers to CERT has been criticised by NGOs as being cynical, despite their having operated within the rules of the legislation. With hindsight, the legislation appears naïve if we assume the utilities will choose the lowest cost means of compliance and the lessons from the previous DSM programmes appear have not been learnt. CERT has not caused the ‘big six’ to engage in a significant shift to energy service provision; however the continued presence of targets, with government efforts to improve compliance, may drive suppliers to deliver more effective measures. In the longer term these incremental changes look unlikely to change embedded cultures significantly.

In summary the policy responses to climate change circa 2010 do not challenge the supply paradigm and consumers continue to be largely detached from climate change mitigation and the associated decision-making processes. While the notion of consumer choice is common parlance in energy policy circles, there is very little choice 'on the ground'. Energy efficiency through CERT is paid for by every customer, but not all customers benefit. The labelling scheme has become largely ineffective with choice almost eliminated. These issues will, in turn, to some extent further tarnish perceptions of the consumer and the viability of demand side programmes in general. Critics of the existing approaches argue that the policy development is flawed from the outset, since they are framed by negative perceptions of the consumer, and that more nuanced approaches are required to deliver genuine change. Moreover consumers’ perceptions of the suppliers, ‘in trust deficit’ impinge on the effectiveness of delivery.

We can now advance the contention that this ‘decoupling’ of the supply and demand sides is in part both encoded in, and promoted through meter technology. The familiar ‘Ferraris’ electricity meter pre-dates climate change and market liberalisation, and energy markets and commercial systems have developed with a minimal interface to domestic consumers. The incumbent metering system excludes any possibility of short-term price elasticity by failing to offer any incentive for load shaping. Infrequent
inaccurate billing, limited tariff variation and limited information all interfere with longer term choices and dampen the scope for consumer adaptation. In a sense, the ‘information deficit’ model of the consumer is a self-fulfilling prophecy made true through the historic choices in system development. This has engendered a lack of demand response, which is now taken by policy actors to be a feature of the consumer not the system; ‘electricity demand is inelastic’ (Ofgem 2006), despite evidence to the contrary (Darby 2001).

The practices of measurement in metering and labelling as discussed represent formal processes encoded in law, consistent with the responsibilities of the state. Approaches to modelling are more diverse, are often institution or discipline specific, and can be both formal and informal. The ‘rational consumer’ represents a conceptual model of the individual that is consistent with free market ideology, and importantly makes econometric modelling possible. Social, cognitive and behavioural psychologies present us with a far more complex range of mental models of the individual, and while not providing a unified framework, they do offer insight into the complexities and commonalities of human behaviour. Similarly, theories of persuasion are related to the disciplines of psychology and can be empirically verified. In current approaches to the management of the electrical system, the complexities of the human aspects of the demand side are largely ignored in favour of predicting demand based on historic trends\textsuperscript{75}. Using these assumptions it has been possible to design and manage the national system effectively; however it is conceivable that these abstract models, and specifically the domestic profile class demand curves, also engender a perception of the ‘disengaged consumer’ in the minds of the ‘system builders’.

In summary, measurement and modelling not only provides data regarding specific interventions, but also contribute to the understanding, or ‘mental models’ of the wider system, which in turn can influence the institutional and developmental cultures. Against this backdrop the European Union is pushing for a more engaged public and greater involvement of the ‘demand side’, most notably through the ESD. The directive has resulted in a lengthy negotiation of the future of electricity metering in the UK.

\textsuperscript{75} Albeit adjusted according on other variables, for example weather data.
9.3 The prospects arising from advanced metering

Historic events, such as the privatisation of the UK electricity sectors, or the arrival of new technology, have been hailed as promising opportunities for improved demand side management and increased consumer participation. Guy (Guy 1994) proposed that privatisation could herald a new era of DSM with the formation of Regional Electricity Companies (RECs) providing a driver for IRP type activity. This optimism was shared by government who thought that post privatisation consumer demand would drive differentiation in energy services (Government 1996). With hindsight, the effects of these changes have been overstated and little has changed on the demand side, other than, for example, the consumer’s ability to switch supplier. This suggests that institutional inertia is sometimes underestimated as an influence in energy system development; or that the model of competition in the electricity sector has not stimulated service differentiation.

What social science analysts would typically describe as a positivistic analysis, continues in the contemporary policy discourse. For example, Darby argues that social ‘tipping points’ can cause a cascade of change in attitudes and behaviour, suggesting the possibility of rapid change in energy culture (Darby 2005). Sauter proposes that micro-generation could represent a radically ‘disruptive technology’ and cause the electricity system to be significantly reconfigured (Sauter and Watson 2006). However such analyses are typically tempered with consideration of the importance of roles and responsibilities of government, private sector actors and consumers.

A change in metering arrangements might provide an opportunity to engage in a new era of DSM, where individual households play a significant role in emission reductions. However, such a change would require a significant re-configuration of the wider system at a number of levels including technology, institutional cultures and responsibilities. It is not clear then that a change in technology alone will deliver any radical transformation in ‘energy culture’, although metering, if appropriately specified will be a key component in delivering significant change.

The debate surrounding ‘smart meters’ was strongly influenced by conflicting supplier and government points of view. While the government idealised the notion of
metering competition, consistent with existing legislation, the suppliers identified the manifold operational complexities that it entailed. The pace of metering policy development was retarded by the government initial ‘arms length’ approach, and a lack of UK evidence with regards to the benefits of metering. In terms of carbon emissions the debate was more muted, and was poorly informed in terms of evidence regarding demand response and was biased toward the ‘waste narrative’ as discussed. In the commercial and industrial sectors, metering data provide the basis for interventions relating to power quality, load profile shaping, shaping employee behaviour and choices in plant components and integration. Sub metering of plant is often justified on cost grounds, allowing the identification of contributing loads and their relative cost.

Conversely the domestic setting comprises a range of comparatively small loads, with homes configured in a similar manner to each other. These loads do not warrant permanent sub-metering on cost grounds because the user has little influence over their consumption other than through whether the appliance is used or not. Advanced metering is proposed as a means to engage users with their overall usage and the relative power consumption of various appliances, while also allowing the utility companies to provide accurate and more informative billing. However the debate surrounding metering has largely been around ‘if’ as opposed to ‘what’ metering should be rolled out. For example, little attention has been given to the issues of power quality and load shaping, despite their importance in C&I demand management and supply side economics. This bias is consistent with an energy market where one of the biggest causes of customer complaints is incorrect billing largely due to estimated readings, a problem that would be rectified by automatic meter reading.
9.4 Beyond ‘behaviour shaping’

In the final months of the Labour Government in 2010, the then recently formed Department for Energy and Climate Change (DECC), moved the Government’s stated position from a seemingly ambivalent to a more positive stance. However, other than the notion of ‘smart meters’ being an essential component of ‘smart grids’, little specific detail was provided.

While advanced metering technology alone may not be sufficient to evoke a systemic change, it does represent an ‘interstitial enabler’ working between systems, as described by Joerge and Shinn (Joerges and Shinn 2001): in this respect it could potentially be involved in reconfiguring energy systems at a number of levels from the technical to the institutional and cultural.

The list below attempts to identify some of the technical and cultural benefits that might result from the widespread adoption of advanced metering and associated services:

- Reduced waste through short term feedback; for example a visual display.
- Peak demand reduction and improved system load factor through TOU or CPP.
- Demand response through short term feedback; for example a visual display.
- Demand response through automation.
- Reduced waste through long term feedback; for example billing.
- Buying habits improved through ‘energy literacy’.
- Identification of appropriate interventions within the home.
- Improved incentives for micro-generation.
- Identification of target households for intervention by third parties.
- Temporal and spatial identification of losses.
- Appliance fault identification.
- Improved demand profile data for evaluation and research.
- Appliance designs becoming sympathetic to the wider system.
• Improved supplier understanding of the consumer.
• Improved consumer understanding of electricity use and environmental outcomes.

The extent to which such benefits accrue will depend on the final specifications of the metering system, the access to information by different actors, the response of the suppliers to the technology, and in turn the consumer’s response: all of which could either present barriers to system development or spur innovation. Historical analysis shows us that well-intended policy can result in unintended consequences, and despite the more positive government position with regard to metering, the suppliers hold the strongest hand in term of shaping the outcomes. The suppliers are legally responsible for metering and have dominated the debate, and it is not clear to what extent suppliers will advance TOU tariffs or CPP.

Whilst waste reduction has been cited as the main environmental benefit of ‘smart metering’ the subject is far from having been exhaustively investigated. For example the variable results from direct feedback schemes may be due to a lack of attention to, or differentiation of, the communication process. Obvious waste, for example leaving lights on, will diminish as a corollary of lighting becoming more efficient, as will standby power for consumer electronics. However less obvious waste like that embedded in cooking habits, for example not putting a lid on cooking pans, may be an appropriate target for shaping behaviour through media campaigns. It is however worth noting the ‘double dividend’ of improving the efficiency of domestic lighting: as a corollary of their function and social norms, lamps cause demand at morning and evening ‘peaks’; thus lighting regulations will have the effect of reducing peak without the need for TOU pricing and metering. This said TOU tariffs might encourage substitution of more efficient lamps and waste reduction due to the higher prices. This logic also holds for cooking with gas as opposed to electricity, but as discussed earlier fuel substitution is not promoted by current policy. Again, here we see subtle differences between the various energy services and the means to minimise their impacts.
Electricity bills could also provide a source of consumption feedback, but again this is not an area that has witnessed significant innovation or research. Behaviour shaping, in both the short and longer terms, as a means for demand side management might have more potential than existing studies suggest. Moreover improved responses might be achieved with more attention to the communication and persuasion processes. These processes may in turn benefit from improved metering data. High resolution sampling of domestic demand might provide an opportunity for identification of inefficient appliances and/or behaviour. Profiles could be inspected by professionals, or non intrusive load monitoring conducted automatically, to offer tailored advice and tariffs.

Outside the energy market, research efforts could also benefit from high resolution demand profiles of individual dwellings and communities. Using data from a specific community it would, for example, be possible to evaluate more accurately the benefits of renewing cabling or transformers, or the addition of local generation technology or energy efficiency measures. While data will be abundant if a roll-out of smart metering occurs, it is not clear if these will be made available to the research community. Moreover, given the supplier’s dominant position in the metering debate, metering specifications risk being limited to half hour resolution as per the wholesale market.

Beyond these specific benefits, in the long run advancements to the 3Ms may provide wider cultural and institutional benefits. For example the culmulative experience of gained from improved metrology may break down the negative pre-conceptions of the ‘demand side’ as discussed earlier.

### 9.5 Closed loop systems

In the domestic sector, demand side interventions have typically not involved site measurement of energy use. This simplifies the process of delivery, but obscures the success or failure of specific interventions. The C&I model of energy management centres around measurement, which has been identified as essential for both accounting and participation. Firstly, all interventions require ex-ante and ex-post
measurement by the energy manager in order to identify inefficiencies and validate results. Secondly, interventions themselves may include measurement processes, for example with employee engagement facilitated through feedback and reward.

These processes represent closed-loop systems, where interventions can be dynamic processes, where actors respond to changing conditions and the interplay of different factors\textsuperscript{76}. This is distinct from the domestic setting, where efforts have involved open-loop systems, where static-passive measures are delivered but not monitored. The widespread adoption of modern AMR metering technology could facilitate a change from open loop to closed loop management, whereby with appropriately specified metering, householders or third parties on the consumers behalf could perform short and long term \textit{ex-ante} and \textit{ex-post} analysis.

9.6 Beyond metering

9.6.1 Responsibility: Supplier or consumer?

The idea of the ‘demand inelastic, information deficit consumer’ is deeply embedded in policy circles. However, in examining the behavioural and social aspects of demand, this perception of the consumer has been identified as overly simplistic. The review of demand side issues above has revealed the proliferation of appliances, the complexity of influencing behaviour, with social and institutional effects causing a ‘dynamic lock-in’ to consumption habits. Industrial and commercial firms that face significant energy costs will, in the pursuit of profit, substitute fuels and implement energy efficiency measures. It is not clear that homes are run on a similar basis, and energy cost may represent only a small part of the family budget. The powerful effect of social norms leads us to acquire new technologies and their use becomes a way of life, especially with regards to ‘time using’ technology. Yet consistent with historical approaches, the UK government has largely avoided engaging the consumer and instead made energy suppliers, and to a lesser extent, appliance manufacturers, responsible for managing demand\textsuperscript{77}.

\textsuperscript{76} For example weather or fuel prices.
\textsuperscript{77} Albeit in accordance with European legislation.
A weaker policy assumption is that appropriately informed consumers will adjust their attitudes and behaviour, becoming more energy efficient. Such changes are promoted with the justifications of saving money, as per the rational consumer, or helping ‘the environment’. Given the current relatively low cost of energy, efficiency actions will only yield relatively modest cost benefits and may only be of interest to the poor. Conversely the environmentally conscious consumer may participate in carbon emission reductions even if it increases his energy costs, for example through ‘green tariffs’.

While current policy interventions may only moderately reduce carbon emissions, the visible actions of government and commercial actors do help to maintain their legitimacy. From the consumer’s perspective, ‘green’ options on the high street or from utilities, allow the environmentally concerned to feel that they are making positive consumption decisions and have some agency. However, despite the overwhelming scientific consensus on climate change, the general public is divided as to its causes and effects. This is sometimes attributed to a lack of understanding; however this may also be due to aspects of human psychology. Consistent with cognitive dissonance theory, as climate change science reveals an ever growing need for a change, so denial and other defence mechanisms will increase to resolve the conflict between government aspirations and actuality.

In the longer term it seems unlikely that relying on supplier DSM activities and ‘green’ consumer choice will provide the drastic carbon emission reductions required. Moreover, it will no longer be adequate simply to ascribe the consumer as in denial, uninterested or unmotivated. In the current market framework, electricity suppliers must deliver energy efficiency and renewable energy, in parallel with their efforts to sell energy. Targets are met, but ‘market transformation’ has not developed to the extent that energy companies are involved in energy service provision as opposed to energy supply.

If we accept that there are problems with what are currently supply-centric and ‘technology push’ approaches, a primary question emerges: ‘Can 2050 emission

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78 Companies such as Good Energy claim that all their delivered electricity comes from renewable sources.
reduction targets be achieved without a change of roles and responsibilities?’ or more specifically ‘Would it be more appropriate to engender decentralised responsibility and corresponding market pull?’

Qualitative research conducted by Ofgem in 2009 revealed that consumers themselves believe that compulsion through government intervention will be necessary:

‘There was an assumption made very early on in the discussion that people will be forced into making greener choices through legislation, and these workshops show that consumers believe that there will be an increase in Government involvement, which is deemed necessary over the next 20 years. Panel members agreed that overall consumers need more information and support to have the power to make the ‘right choices’ when it comes to energy, as well as changes to the physical and market infrastructure to ensure they can act effectively. It is expected that this will need to be driven by the Government.’

(Opinion Leader 2009)

While perhaps politically untenable at present, in the longer term, some form of rationing, or taxation of carbon emissions, would represent a significant shift of responsibility from the utilities to consumer. Such approaches could in turn provide a strong signal to all service providers to minimise their carbon intensity per unit output as opposed to simply achieving targets. Whatever technology or market mechanisms come into play, if carbon emissions are to be reduced, energy costs are likely to rise, at least in the short to medium term\(^{79}\), due to the scarcity of low carbon supply, limited energy efficiency options, and the incumbent systems inertia to change. With rising costs, the consumer would be more naturally engaged in budgeting of carbon and related decision making, representing a significant change in the consumer’s relationship to energy services. Energy accounting could become increasingly important for the consumer, in order to balance their ‘carbon budget’ and make consumption and substitution decisions. Such a scenario could also provide stimulus for ‘market pull’ for energy efficiency and micro-generation, in turn increasing the

\(^{79}\) In the longer term low carbon energy might become abundant and low cost.
information needs of the consumer. Moreover the diversity of actors in a mass movement could spawn a wider range of innovation with solutions better tailored to individual circumstance. This is distinct from IRP type approaches seen in 2009, with for example, the distribution of free CFLs under CERT. Moreover, a more consumer centred approach, could increase participation and innovation whilst not fundamentally challenging market ideology.

Rather than be engaged in day to day detail of DSM, some consumers might decide to delegate modes of participation to a third party through for example an ‘Energy Services Company’ (ESCO). In improving metering and reducing estimated billing energy suppliers may become more trusted actors and better able to deliver advice and services. However, as discussed earlier, the consumer needs to be understood, with communication methods and content, tailored to the individual and delivered by a trusted actor. Suppliers are currently in a weak position in terms of public trust, so are not a natural candidate for managing DSM activity.

The problematic notion of the consumer characterised as being in ‘information deficit’ is distinct from the issue of whether the consumer would benefit from further information. Criticism of the ‘information deficit’ model of the consumer does not extend as far as to deny the benefits of information provision; rather it questions the stereotyping of the consumer and this emphasises the need for targeted rather than generalised demand side programmes.

### 9.6.2 Developing the evidence base

Looking beyond current approaches to system development, be it a more participatory future or a move to utility controlled DSM or decentralised energy, new approaches to the 3Ms will become both possible and necessary. What demand side management and decentralised energy systems are appropriate remains an open question, requiring further analysis and comparison with ‘supply-centric’ scenarios (Bilton, Ramsay et al. 2008). While a centralised ‘system builder’ can treat consumers as one homogenous

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80 In the right regulatory and economic environment, energy service companies might offer an intermediary role between consumer and energy suppliers, offering efficiency measures against a share of expected savings.
group, to understand decentralised systems requires consideration of local social and technical diversity. If there is a change of emphasis towards local systems, the ‘system builders’ will themselves become more numerous and disparate, increasing interest in the technology, economics and operation of decentralised alternatives. Moreover if we treat electricity demand as a uniform commodity with inelastic demand we inadvertently obscure the rich diversity of the demand side. Surely it is services, for example heat light and refrigeration that people want, not electricity, and each service type will have its own elasticity, and options for efficiency and substitution.

The previous sections discussed how from a LTS perspective, metering and labelling schemes create system inter-dependencies with associated inertia to change, as well as, on a practical level, obstacles in the pursuit of a low carbon electricity system. They also frame the perception of what is possible through the perceptions of cumulative experience. The norms of the supply paradigm, through the institutional ‘embedding’ process also extend into the research community. Approaches to measurement and modelling are typically consistent with those used within the power sector and may have a limiting framing effect on our evaluation of alternative paradigms. It follows that interventions that can be modelled will gain preference over those that cannot.

Renewed interest in the ‘demand side’ has given rise to higher resolution models, typically with sample periods in the order of minutes. Empirical work however has indicated that domestic power flows can vary considerably in periods of seconds or less. The half hourly approach to modelling is appropriate if the intention is to analyse the effects of changes to the national demand profile ‘post diversity’, but it necessarily masks localised effects.

If a significant shift is to occur towards demand side activities, there will be a growing need to understand the nature of energy flows at a local level. The move from the macro to the micro requires a change of emphasis of measurement and modelling, if we wish to understand the effects of load shaping, micro-generation, storage and energy system integration. Moreover, constraints such as low voltage (LV) network

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81 For example with University training mirroring existing practices.
capacity and voltage regulation must be considered in any significant reconfiguration of the demand side and previous assumptions may no longer be valid.

The interstitial nature of technical losses, which in practice causes a ‘smearing’ of the costs and benefits of mitigation, may explain the lack of related analysis. As with the RO and ETS, these costs are passed on to the consumer, with no option for participation. Metering could provide both a means to participate dynamically in the reduction of losses, for example through TOU metering, as well as furnishing DNOs with information that could help identify where losses occur and improve investment decisions. However, the new metering technology developed in the incumbent centralised paradigm may not exceed the requirements of commercial retail systems and additional features valuable for research, such as higher time resolution, or reactive power measurement may not be specified. Given the above, following a widespread roll out of ‘smart metering’ there is likely to still be value in empirical survey work, sub-metering and software modelling of interventions.

Conversely, in the event of a high specification metering roll out, software modelling will still be of value. Firstly, where the costs of physical pilot studies are prohibitive and secondly, the new wealth of data will require new frameworks for its utilisation in research. Modelling allows hypotheses to be tested without expense of physical experiments; metering provides data which allows calibration of models and the testing of actual interventions.

9.6.3 Understanding local systems

To understand the implications of local interventions we cannot evaluate only the demand profile of an individual home, since losses on the local cables are dependent on other loads in the neighbourhood, and these loads depends on the behaviour of different households and their appliance population. Costs and benefits will differ for different network configurations, appliance populations, household demographics, lifestyles and habits. Conversely, by analysing a neighbourhood, we can test both the local net efficiency of local systems and changes in load shape seen by the wider system. In analysing interventions at the home or the neighbourhood level, it may be

82 Meaning that cost and benefits are spread between many agents.
possible to apply approaches used in the C&I sectors, although as little is known about the temporal or phase detail of domestic loads it is not certain what approaches might be valid. For example, it is not clear if reactive power is a significant factor in the domestic sector, or if there is enough deferrable demand to warrant load shifting.

Interventions to be tested might relate to appliance technology, human behaviour or a combination of approaches. Moreover interventions targeted at different energy services might warrant different approaches, for example:

- Lighting, from static efficiency (regulation or competition) and less wasteful behaviour (knowledge transfer).
- Cooking from behavioural change (knowledge transfer).
- Refrigeration from static efficiency improvements (regulation or competition), dynamic efficiency (for example with grid balancing) and better location in home (knowledge transfer).
- Laundry through static efficiency, habits, hot water system integration, or dynamic efficiency through deferral and avoiding peak.

Laundry is an interesting end-use in that, it is energy intensive, can be deferred (Lampaditou and Leach 2005) and the process modified in both technological and behavioural terms.\(^\text{83}\) The value of behavioural measures might be explored in terms of ‘if person X’s washing machine operated off peak instead of peak what would the benefits be’. This is distinct from survey type analyses which aim to establish what people would do in a given situation; however these two approached can be combined.

Automated, that is passive-dynamic measures actions will clearly have cost and benefits, but these are not yet as clear as compared to those offered by static measures. For example a washing machine could contribute to demand peak reduction, system balancing and distribution loss reduction. Which of these is appropriate depends on what services the washing machine can provide to the system, its relative value and the cost of implementation. This said passive-dynamic measures

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\(^{83}\) See the section in chapter 3 regarding the evolution of washing machine technology.
can be accurately modelled because they do not require changes in human behaviour, thus different measures can be modelled that accurately reflect feasible technologies.

Give the broad scope of options for demand side participation it appears that there is value in extending the bottom up modelling tradition to aid demand side research. Specifically, this might include: improving the time and phase resolution of bottom up modelling, paying attention to the effects of the network and variances in appliance design. Before such efforts can commence a deeper understanding of domestic appliances is required: to this end, the following chapter investigates the power flows in typical domestic appliances.

The following chapter then integrates these findings into a modelling framework that allows the creation of model neighbourhoods, synthesis of demand profiles and a means to evaluate interventions. The framework is then tested with some simple case studies.
10 Power flows in contemporary domestic appliances

Over the previous chapters, energy measurement has been mainly discussed in terms of kWh, GWh or MTOE, metrics suited to the consideration of energy as a commodity. Power flow on the other hand tends to be represented in terms of diurnal load curves, be it kW per house, or GW at the national level. Research into the modelling and shaping of diurnal load profiles has typically focussed on time resolutions of 1 hour, \( \frac{1}{2} \) hour, \( \frac{1}{4} \) hour (Capasso, W. Grattieri et al. 1994; Willis 1997), consistent with the needs of centralised system management.

More recently, renewed interest in decentralised energy and demand side management has resulted in the development of models with higher resolutions, in the order of minutes (Stokes, Rylatt et al. 2003; Richardson, Thompson et al. 2007). Observation, such as those of the agitation cycle of a washing machine, or the visible pulsing of a ceramic hob, indicate that the switching period of some domestic loads can be in the order of seconds. Literature describing domestic loads at this resolution is scarce and possibly for a number of reasons: data collection is problematic and time consuming as discussed earlier; data are of little interest to centralised system operators; and test apparatus is expensive.

To extend our understanding of power flows in the home this chapter presents the findings of a survey of common domestic appliances. Collecting this data is difficult because of the limited availability of access to the appliances, thus a number of approaches were adopted. Power flows were recorded opportunistically, based on access to the appliances owned by the author’s friends, relatives, with an additional source being a second hand electrical goods shop. Appliances were monitored only in situations where the appliance plug and socket were easily accessible\(^{84}\). While this approach risked statistical errors in sampling, for example access to very modern appliances was limited, it emerged that there is similarity amongst different brand variants, suggesting common approaches to design between competitors.

\(^{84}\) Access to appliances plugs and sockets is not always straightforward. For example access is often obstructed by furniture such as book cases which cannot easily be moved.
An additional problem in capturing demand profiles for in situ lights, cookers and boilers is that their power is typically not provided through a plug socket. To avoid interfering with any house wiring, a collection of lamps and cooking appliances were acquired and connected to three pin plugs for testing. In addition to collecting power flow data, a small number of wet appliances were measured for water usage. Data was also augmented with technical product information.

10.1 Power flow measurement

10.1.1 Test Apparatus

The data presented in this chapter was collected using a Chauvin-Arnoux CA884B power analyser (CA). The CA is a portable device with batteries, designed for engineers in the power sector and has a range of settings, including the ability to calculate and record the phase and harmonic content of a load. It has a minimum sample period of 1 second and can record a 24 hour trend at this resolution provided a limited dataset is selected.

![Test apparatus](image)

Figure 25 Test apparatus

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85 Kindly provided by Prof. Tim Green of Imperial College.
86 Described in more detail in the following section.
Although at the time of writing the CA represented the state of the art in portable power analysers, it is designed primarily for high power applications, and its probes and recording ranges were not ideal for domestic application. Initial experimentations revealed two issues were impinging upon the accuracy of recording:

- The 100Amp probe setting resulted in low power data being lost, since the CA stops recording at a threshold current flows of 0.1A.
- A more sensitive probe setting of 5A allowed the recording of low level currents but would saturate under higher loads.

Figure 26 shows a ‘break-out box’ designed by the author to overcome these shortcomings. While making the voltages and current available to the power analyser in a safe manner, the panel also provides an eight winding current coil, which allowed the 100A range to be shifted down to 12.5A.

This approach lowers the recording threshold from 0.1A to 0.0125A, and in practice, no appliances compatible with a 13A socket exceeded a 12.5A current rating. Higher currents, for example cookers could be recorded using the single cable retaining the 100A probe range. Electronic goods where tested using a 5amp range probe setting, recording at 100x, affording high resolution for low level signals. Using these
different approaches meant that the recorded data was not recorded at the correct scale by the power analyser and the scaling of data values had to be managed. To this end, rather than manipulating the original data, the data was kept in raw form, with configuration data recorded to allow automatic software calibration.

10.1.2 Reactive Power

Reactive power is a term used to describe power flow on the electricity system where current flow is out of phase with the voltage; it causes losses and takes up network capacity whilst not providing useful energy (Willis 1997). Reactive loads are caused by components within an appliance that cause inductance or capacitance; motors are a common source of reactive power flow. Industrial users of energy are metered for both active (useful power) and reactive power, whereas the domestic sector is only metered for active power.

In a mainly resistive load, for example a kettle, the amplitude of current follows the oscillating mains voltage, and the voltage and current are said to be in phase. However if an appliance contains a reactive components the current flow is said to ‘lead’ or ‘lag’ voltage.

Figure 27 shows a capacitive or leading current and the resulting power flow.
The apparent power (S) is the product of V and I. In figure 27 the value of S is negative for a part of the cycle, between the points where I and V fall below zero, this is an indication of reactive power flow. The reactive component flows into and then out of the load, as opposed to providing useful energy. Power flow can be described using a vector diagram, as shown in figure 28, that expresses the relationship between active power P (Watts), reactive power Q (VAR\textsuperscript{87}), and apparent power S (VA).

\textsuperscript{87} Voltage Amps Reactive
Reactive power flow is typically described by the phase angle (theta), or power factor which is the ratio of active to apparent power (P / S).

10.1.3 Harmonics

A further complication in analyzing power flow is when current flow is non-sinusoidal. Non sinusoidal current flows can occur through voltage distortion introduced by passive components such as transformers, but are largely introduced by non-linear loads. This is increasing an issue as more benign passive loads are substituted with electronic devices.

For example, incandescent light bulbs operate at unity power factor, and as such can be described as a simple resistance. Conversely alternatives often have poor power factors and sometimes high total harmonic distortion (THD) (Verderber 1993; Fassbinder 2004).

For example, figure 29 shows a screenshot from a power analyser, in oscilloscope mode, measuring the power flow to a 20W CFL. The paler line represents voltage and the darker line current. To maintain resolution this was recorded with a 100x current multiplier, hence the high amperes value in the image.

![Oscilloscope view of voltage and current through example CFL (x100)](image)

Figure 29 Oscilloscope view of voltage and current through example CFL (x100)
There are two important aspects to this current waveform:

- The current flow is out of phase with voltage, it leads voltage.
- Harmonics can be identified by the non sinusoidal current waveform.

Figure 30 presents the same information but in the frequency domain. Each vertical bar represents a frequency component of the current flow, the Total Harmonic Distortion (THD) figure of 155% tells us that the majority of current flow is harmonic.

![Figure 30 Spectral analysis of the current waveform in figure 29.](image)

Since the 3rd harmonic is selected, we can also see that it has a +177° phase shift from the current fundamental. Moving up through the other harmonics a range of phase shifts are found.

The fundamental (1st harmonic) with phase shift and harmonics combine with other current flow on the network having a local and network level effect (Verderber 1993). Harmonic current flow distorts the local voltage waveform if there is significant impedance seen at the voltage source, and this can interfere with equipment operation. However it has been shown that with a mix of appliances harmonics can to an extent cancel each other resulting in a reduced net power flow (Demoulias, Kampouri et al. 2008).

Since the harmonics from any given appliance mix with other power flows on the network, and are progressively attenuated by passive components in the system, they
are largely responsible for localised effects. Aggregate power flows on the wider network are more sinusoidal, albeit with associated phase shift (Fassbinder 2004). Third and triple harmonics present a particular problem in that they can be additive in the neutral, increasing neutral current flow and voltage distortion (Coates 2007).

In practice, because of the presence of harmonics, there are two approaches to calculating reactive power flow:

- **Apparent power factor**: where power flow attributed to harmonics is included in the calculation of S.
- **Displacement power factor**: where S is calculated from fundamental frequency power flow only. In addition THD can be used to separately describe the harmonic content.

If the CA was set to record using the former method, then it would not possible to differentiate between current phase shifts and harmonic power flow. Alternatively if the later approach is used it is possible to calculate both the apparent and displacement power factors from the data recorded.

In the appliance survey and modelling to follow, the later approach is taken since we need to understand the sinusoidal component seen by the wider system separately from any localised effects. Moreover, the modelling of harmonic current flow involves complex calculations, with each harmonic having a phase shift and different harmonics potentially flowing in different directions to the fundamental.
10.2 Findings

10.2.1 Lighting

A range of bulbs types were tested, and as demonstrated in figure 31, they present very different load profiles. The main focus of testing was on compact fluorescents as they are the most common alternative to the incandescent. From the small sample group there was a noticeable difference between the older and newer CFLs. More recent variants had a smoother current peak as demonstrated in figure 31. This apparently modest change has a dramatic effect on reducing the higher frequency harmonics. Except for the variance described, all CFL had very similar signatures.

Traditional fluorescent lights have lower harmonic flow, but current lags and reactive power exceeds active power flow. The transformers used for low voltage halogen lights also cause lagging power flow. Conversely electronic power supply alternatives demonstrated a more sympathetic profile, approaching an in phase sinusoid.

Table 29 Power flow in various lamp types.

<table>
<thead>
<tr>
<th>Appliance</th>
<th>W Ave</th>
<th>VAR Ave</th>
<th>VAAve</th>
<th>dispPF</th>
<th>theta</th>
<th>truePF</th>
<th>THDAve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light_CF_SE249BB_1.csv</td>
<td>11.44956</td>
<td>-4.66288</td>
<td>22.82279</td>
<td>0.926142</td>
<td>22.1588</td>
<td>0.501672</td>
<td>155.1812</td>
</tr>
<tr>
<td>Light_CF_SE249BB_2.csv</td>
<td>11.04947</td>
<td>-5.39711</td>
<td>19.14003</td>
<td>0.89854</td>
<td>26.03317</td>
<td>0.577296</td>
<td>119.2718</td>
</tr>
<tr>
<td>Light_CF_SE249BB_3.csv</td>
<td>11.18067</td>
<td>-5.9631</td>
<td>18.02429</td>
<td>0.88235</td>
<td>28.07281</td>
<td>0.620311</td>
<td>101.1589</td>
</tr>
<tr>
<td>Light_CF_SE249BB_4.csv</td>
<td>10.86167</td>
<td>-6.02935</td>
<td>20.52444</td>
<td>0.874321</td>
<td>29.03525</td>
<td>0.529197</td>
<td>131.5164</td>
</tr>
<tr>
<td>Light_CF_SE249BB_5.csv</td>
<td>11.87298</td>
<td>-6.20419</td>
<td>20.3565</td>
<td>0.886291</td>
<td>27.58917</td>
<td>0.583252</td>
<td>114.4152</td>
</tr>
<tr>
<td>Light_CF_SE249BB_6.csv</td>
<td>11.1342</td>
<td>-5.311</td>
<td>19.90341</td>
<td>0.902577</td>
<td>25.50109</td>
<td>0.559412</td>
<td>126.6171</td>
</tr>
<tr>
<td>Light_CF_SE249BB_7.csv</td>
<td>11.47273</td>
<td>-5.84116</td>
<td>19.75894</td>
<td>0.891148</td>
<td>26.9822</td>
<td>0.580635</td>
<td>116.4282</td>
</tr>
<tr>
<td>Light_FL_SE249BB_1.csv</td>
<td>128.9908</td>
<td>130.2357</td>
<td>188.3141</td>
<td>0.703703</td>
<td>45.27514</td>
<td>0.684977</td>
<td>23.54221</td>
</tr>
<tr>
<td>Light_LED_SE249BB.csv</td>
<td>2.830448</td>
<td>-16.4728</td>
<td>17.5565</td>
<td>0.169344</td>
<td>80.25032</td>
<td>0.161219</td>
<td>32.14473</td>
</tr>
<tr>
<td>Light_LVH_ELE_SE249BB.csv</td>
<td>56.5356</td>
<td>0.182769</td>
<td>56.91544</td>
<td>0.999995</td>
<td>0.185225</td>
<td>0.993326</td>
<td>11.60671</td>
</tr>
<tr>
<td>Light_LVH_TRN_SE249BB.csv</td>
<td>15.31187</td>
<td>10.85093</td>
<td>19.33339</td>
<td>0.815898</td>
<td>35.32372</td>
<td>0.791991</td>
<td>24.75567</td>
</tr>
</tbody>
</table>

CF = compact fluorescent
FL = tube fluorescent
LED = light emitting diode
LVH = low voltage halogen (ELE with electronic supply) (TRN with transformer).

Table 29 show the various lamps measured and their corresponding power flow characteristics.
Figure 31 Power flow profiles for a range of alternative lighting technologies.
10.2.2 Cooking

As with lighting appliances, access to the power supply of ovens and hobs is often limited by the lack of a plug and socket. Because of this only two electric ovens were monitored, and to better understand hobs, a two ring portable standard electrical hob, and a second hand ceramic hob were purchased.

10.2.2.1 Conventional Hobs

Figure 32 represents the power flow in a hob nominally rated at 1.5kW, heating a pan of water.

![Figure 32: Power flow in an electric hob for 2 settings.](image)

We can see that at the demand profile changes in two ways as the setting is increased, firstly the ‘on’ period increases, secondly, the total ‘on-off’ period decreases. This is consistent with thermostatic behaviour in that, the higher target temperature necessitates more energy and the temperature of the hob will fall below target more rapidly than on lower settings.

If we assume that the thermal mass and thermostat dictate the switching behaviour, the hob will respond to lower system voltages by remaining on for longer and visa versa. Conversely the ‘off’ period will remain similar since this is not a function of the voltage but the thermal loss characteristics of the pan and contents in question.
Given the above we can classify the thermostatically controlled hob as constant energy over time, fixed impedance, with variable pulse width. No significant reactive power flow was measured. Earlier work using lower time resolution has estimated the duty cycle of hob to average at 50% (Mansouri, Newborough et al. 1996) to calculate total annual demand. This appears to be an over estimate because the hobs tested only achieve a 50% duty cycle when set to near full power.

Table 30 shows the switching frequency of the hob measured at a range of settings.

### Table 30 Standard hob switching times in seconds for various settings.

<table>
<thead>
<tr>
<th>Hob</th>
<th>lowPeriodAve</th>
<th>highPeriodAve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cook_HOB_1000_SE249BB_1.csv</td>
<td>834</td>
<td>65</td>
</tr>
<tr>
<td>Cook_HOB_1000_SE249BB_2.csv</td>
<td>257</td>
<td>76</td>
</tr>
<tr>
<td>Cook_HOB_1000_SE249BB_3.csv</td>
<td>230</td>
<td>100</td>
</tr>
<tr>
<td>Cook_HOB_1000_SE249BB_4.csv</td>
<td>178</td>
<td>98</td>
</tr>
<tr>
<td>Cook_HOB_1000_SE249BB_5.csv</td>
<td>184</td>
<td>92</td>
</tr>
<tr>
<td>Cook_HOB_1000_SE249BB_6.csv</td>
<td>104</td>
<td>213</td>
</tr>
<tr>
<td>Cook_HOB_1500_SE249BB_1.csv</td>
<td>216</td>
<td>47</td>
</tr>
<tr>
<td>Cook_HOB_1500_SE249BB_2.csv</td>
<td>178</td>
<td>49</td>
</tr>
<tr>
<td>Cook_HOB_1500_SE249BB_3.csv</td>
<td>124</td>
<td>47</td>
</tr>
<tr>
<td>Cook_HOB_1500_SE249BB_4.csv</td>
<td>88</td>
<td>63</td>
</tr>
<tr>
<td>Cook_HOB_1500_SE249BB_5.csv</td>
<td>58</td>
<td>85</td>
</tr>
<tr>
<td>Cook_HOB_1500_SE249BB_6.csv</td>
<td>34</td>
<td>182</td>
</tr>
</tbody>
</table>

#### 10.2.2.2 Ceramic Hobs
Ceramic hobs behaved in a similar way to the conventional hobs, except for that their switching frequency was considerably faster, see table 31.

### Table 31 Ceramic hob switching times in seconds.

<table>
<thead>
<tr>
<th>Hob</th>
<th>lowPeriodAve</th>
<th>highPeriodAve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cook_CERHOB_1200_SE249BB_1.csv</td>
<td>47</td>
<td>2</td>
</tr>
<tr>
<td>Cook_CERHOB_1200_SE249BB_2.csv</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>Cook_CERHOB_1200_SE249BB_3.csv</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Cook_CERHOB_1200_SE249BB_4.csv</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Cook_CERHOB_1200_SE249BB_5.csv</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Cook_CERHOB_1200_SE249BB_6.csv</td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td>Cook_CERHOB_1500_SE249BB_1.csv</td>
<td>590</td>
<td>0</td>
</tr>
<tr>
<td>Cook_CERHOB_1500_SE249BB_2.csv</td>
<td>31</td>
<td>4</td>
</tr>
<tr>
<td>Cook_CERHOB_1500_SE249BB_3.csv</td>
<td>17</td>
<td>4</td>
</tr>
<tr>
<td>Cook_CERHOB_1500_SE249BB_4.csv</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Cook_CERHOB_1500_SE249BB_5.csv</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Cook_CERHOB_1500_SE249BB_6.csv</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>Cook_CERHOB_1800_SE249BB_1.csv</td>
<td>298</td>
<td>4</td>
</tr>
</tbody>
</table>
10.2.2.3 Ovens

Figure 33 shows us that oven power switching behaviour is similar to that of the hob.

Again a thermostatic switch determines a pulse width following a heating up period. The oven in question was a 90cm wide unit with a corresponding higher wattage than the typical 60cm units, which typically operate at around 1 – 2kW. Here we can see that the oven takes a little over 15 minutes to reach temperature, meaning that in some cases the warm up period may require more energy than the actual cooking process.

The waveform in figure 33 allows us to make estimation on the thermal mass inside an oven and its thermal losses. We can suppose that the initial ‘on’ period will be a function of the thermal mass, plus thermal losses, and the pulsing having similar characteristics to the hob.
The power flows described above will be augmented by a reactive component, when the oven is fan assisted.

10.2.2.4 Microwaves

The microwave oven settings tested exhibited either constant power demand or pulsed power. However unlike the conventional oven significant reactive power flow was measured in all cases.

Figure 34 shows us two settings for the same microwave oven. Here we see the microwave causing a pulse of reactive power flow at the outset of the heating period. The 800W setting requires roughly 1200W of power thus is only 60% efficient excluding further losses in transmission to the food. However the microwave does not have to warm up like a conventional oven, with the food being heated directly.
10.2.3 Cold

As with the cooking appliances discussed there is a great deal of commonality between refrigeration devices. All the devices measure presented a cyclic load with high power pulse at the outset of the cooling cycle. Figures 35 and 36 represent the active and reactive power flow for two fridge-freezers, one at least 20 years old the other a more contemporary model. Both recordings include a period where the occupant was cooking dinner and using the fridge.

Figure 35 Power flow in an older fridge-freezer.

Figure 36 Power flow in a typical contemporary fridge-freezer.
In figure 35 from 21:30 to 22:00 and in figure 36 between 19:00 and 19:30 we can see extended cooling period as a result of kitchen activity, highlighting the effect of environmental conditions and door opening.

The modern example shows a well balanced design, where the heat exchange system is such that the minimum compressor wattage is required to that allows a duty cycle of 50%. The earlier model has a slightly over-rated compressor in that it is on for less than 50% of the time. The modern example uses around half the power, compared to the earlier model, and exhibits less reactive power flow, which is most likely managed with the use of a capacitor. Table 32 shows four compressor readings demonstrating different levels of reactive power compensation.

<table>
<thead>
<tr>
<th>Appliance</th>
<th>WAve</th>
<th>VARAve</th>
<th>VAAve</th>
<th>dispPF</th>
<th>theta</th>
<th>truePF</th>
<th>THDAve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold_compressor_A.csv</td>
<td>87.22</td>
<td>16.17</td>
<td>94.86</td>
<td>0.98</td>
<td>10.50</td>
<td>0.91</td>
<td>37.89</td>
</tr>
<tr>
<td>Cold_compressor_B.csv</td>
<td>96.03</td>
<td>70.20</td>
<td>121.16</td>
<td>0.81</td>
<td>36.17</td>
<td>0.79</td>
<td>19.34</td>
</tr>
<tr>
<td>Cold_compressor_C.csv</td>
<td>81.58</td>
<td>-19.13</td>
<td>92.04</td>
<td>0.97</td>
<td>13.19</td>
<td>0.89</td>
<td>45.44</td>
</tr>
<tr>
<td>Cold_compressor_D.csv</td>
<td>165.67</td>
<td>182.20</td>
<td>247.83</td>
<td>0.67</td>
<td>47.72</td>
<td>0.66</td>
<td>11.32</td>
</tr>
</tbody>
</table>
10.2.4 Wet

10.2.4.1 Washing machines
As washing machines provide one of the more complex energy services in the home, and represent a significant part of domestic demand, special attention was paid to sampling multiple machines and multiple setting. During the operation of different washing machines, it was possible to observe signs of energy saving behaviour. Two machines were analysed in detail, recording observations, water flow in and out, as well as electrical power flow characteristics.

Whilst washing machines share many physical features it emerged that there were subtle differences in their operation. For example, heating of the wash can take three basic approaches, namely:

- Heat until target temperature then agitate wash only.
- Heat until target temperature, maintain temperature and agitate.
- Heat until target temperature, agitate, and boost heat half way through agitation period.

Figure 37 represents the latter strategy, as can be seen by the short peak in the middle of the wash. Interestingly, with all washing machines measured, outside of the heating periods, power flow is predominately reactive. In other word the motor power factors seemed to be poorly compensated for.

Figures 38 and 39 show the typical power flow to the motor used to agitate the load (seen between 00:00 and 00:40 in figure 38). These agitation patterns were simple and repetitive during the wash period, and similar in all machines measured. The more complex profile seen at the latter part of the wash comprises 4 rinse and spin cycles with a power spin at the end. Note that as the motor approaches its rated output, in the final spin, it induces less reactive power flow.

The motor rating of 200W is also typical of most machines, with varying levels of reactive power flow compensation.
Figure 37 Power flow in a washing machine on an 40 degree cotton programme

Figure 38 Power flow during 10 washing machine drum rotations.

Figure 39 Power flow during 10 washing machine drum rotations.
Water heating tends to be considered as the major energy use in a washing machine (Goodall 2007) and at higher temperatures this is correct. However, as the temperature of the wash decreases the relative contribution to total demand of the motor increases, thus at 30 or 40 degrees a washing machine motor will consume a similar amount of energy as the heating element. The load presented by the motor also tends to have a poor power factor which may aggravate losses elsewhere on the system. Table 33 lists the observable differences between the two machines that were analysed in detail. Table 34 demonstrates the importance of wash temperature in the energy consumption of a wash.

Table 33 Behaviour of two different washing machines.

<table>
<thead>
<tr>
<th>Wash phase</th>
<th>US Machine circa 2005</th>
<th>German machine circa 2010</th>
<th>Effect of later approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>Machine is filled in one stage.</td>
<td>Water enters drum incrementally.</td>
<td>Initial concentrations of detergent are high, improving wash.</td>
</tr>
<tr>
<td>Heat / Wash</td>
<td>Heating begins after some water has entered drum.</td>
<td>Target temperature is reached before next stage of filling takes place.</td>
<td>Wash is at higher temperature for longer, without using more energy.</td>
</tr>
<tr>
<td>Rinse and spin</td>
<td>Rinses are followed by short spin.</td>
<td>Spins between rinses are faster.</td>
<td>Allows rinsing water use to be reduced since higher speed spin removed more water and detergent.</td>
</tr>
</tbody>
</table>

Table 34 Energy use and reactive power totals for a range of washing machines and settings. Appliance names correspond to the sampled data in the appendix.

<table>
<thead>
<tr>
<th>Appliance</th>
<th>kWh</th>
<th>kVARh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet_WM_SE217DJ_C40.csv</td>
<td>0.362264</td>
<td>0.386081</td>
</tr>
<tr>
<td>Wet_WM_SE217DJ_C60.csv</td>
<td>1.017318</td>
<td>0.834019</td>
</tr>
<tr>
<td>Wet_WM_SE249AF_C40.csv</td>
<td>0.278769</td>
<td>0.167564</td>
</tr>
<tr>
<td>Wet_WM_SE249AF_D30.csv</td>
<td>0.142092</td>
<td>0.040573</td>
</tr>
<tr>
<td>Wet_WM_SE249BB_60S.csv</td>
<td>0.329358</td>
<td>0.107838</td>
</tr>
<tr>
<td>Wet_WM_SE249BB_95PW.csv</td>
<td>2.364998</td>
<td>0.81779</td>
</tr>
<tr>
<td>Wet_WM_SE249BB_C60.csv</td>
<td>1.349007</td>
<td>0.531107</td>
</tr>
<tr>
<td>Wet_WM_SE249BB_C60_2.csv</td>
<td>0.967899</td>
<td>0.418074</td>
</tr>
<tr>
<td>Wet_WM_SE249BB_D30.csv</td>
<td>0.194154</td>
<td>0.248467</td>
</tr>
</tbody>
</table>
10.2.4.2 Tumble Dryers
Tumble dryers exhibit similar load profile to cooking appliances, in that a thermostatically controlled heating element is switched on and off to maintain a given temperature. In addition to the heating element the drum is rotated and a fan is used to extract the humid warm air from the drum. The motor rating can be seen in the troughs of demand when the heating element is switched off. A brief review of spare parts on the internet also revealed that the same motor is often used for both drum rotation and driving the fan. As is seen with cold appliances, there is a sharp peak of reactive power flow as the motor starts up with each new agitation. The appliance peak power of 2.5kW is typical of most contemporary machines. No condensing tumble dryers were available to test.

Figure 40 Power flow in a contemporary tumble dryer.
10.2.4.3 Dish washers
In addition to sampling the power flow to a number of dishwashers, one machine was also monitored for its water input and output flow characteristics, and input water temperature\(^{88}\).

Like washing machines, while machines look very similar, they can exhibit a number of control strategies. From the machines measured, a number of variations in wash programme were identified. Two machines are now described in more detail, with power flows shown figure 41 and 42 respectively.

<table>
<thead>
<tr>
<th>Wash phase</th>
<th>Dishwasher A circa 1995</th>
<th>Dishwasher B circa 2005</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rinse</strong></td>
<td>One rinse is conducted.</td>
<td>Rinse is conducted in two stages, first using all clean water and then discarding some water and filling for a second rinse.</td>
<td>Wash is cleaner before detergent is dispatched.</td>
</tr>
<tr>
<td><strong>Heat / wash</strong></td>
<td>Water is heated to a target temperature and temperature maintained.</td>
<td>Target temperature is reached and then wash continues without the temperature being maintained.</td>
<td>Less energy is used heating water.</td>
</tr>
<tr>
<td><strong>Rinse</strong></td>
<td>Two rinses are performed, a cold rinse and then a hot rinse.</td>
<td>One hot rinse is performed.</td>
<td>By not having a cold rinse the temperature of the washer load is not reduced, and hence needs less heating during hot rinse.</td>
</tr>
</tbody>
</table>

Unlike washing machines, dish washers can be connected to the hot water supply. Figures 42 and 43 represent the load profiles for the same machine on the same setting, the later fed with a hot water supply. The heating of water during wash and the hot rinse at the end account for the majority of the energy use. Comparing these two profiles we can see that increasing the inlet water temperature decreases both energy use and programme duration. In this example total electricity use is reduced by

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\(^{88}\) This was only possible in the author’s home due to the intrusive nature of connecting water meters and collecting waste water in buckets.
around 40%. To calculate the net efficiency would require accounting for the gas heated water, and cost of using hot water for the pre-wash rinse cycle. However it would still appear that using a hot feed is more efficient in terms of carbon than using a cold water feed.

Table 36 Energy use of machines A, B and B with a hot feed.

<table>
<thead>
<tr>
<th>Dishwasher</th>
<th>Appliance</th>
<th>kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Wet_DW_L377AQ.csv</td>
<td>1.863909</td>
</tr>
<tr>
<td>B</td>
<td>Wet_DW_SE249BB.csv</td>
<td>1.332839</td>
</tr>
<tr>
<td>B with hot water feed</td>
<td>Wet_DW_SE249BB_HW.csv</td>
<td>0.835932</td>
</tr>
</tbody>
</table>

The water pump that drives the cleaning rotors consumes around 200W and can be identified by its accompanying reactive power flow. The very small load seen between the troughs in demand is another small pump used to flush the device.

89 Hot water temperature was around 50 degree centigrade.
Figure 41 Power flow to dishwasher A circa 1995

Figure 42 Power flow to dishwasher B circa 2005 with cold water feed.

Figure 43 Power flow to dishwasher B with hot water feed.
As discussed earlier ICT components typically exhibit constant power characteristics in other words, their power consumption does not depend on the system voltage. However their consumption does vary depending on what state they are in and whether how much information they are processing.

In collecting the sample data the author did not wish to interfere with settings of owners computers, and thus only setting used by the owners where recorded. In most cases on, standby, and off modes were recorded\(^9\). In the on mode computers were set to playback internet video in order to load the processor.

Too many ICT appliances were recorded to fit comfortably into a table. The full data set can be found in the appendix, including tabulated averages and raw, pre-scaled data. An example of the data captured can be seen in table 37. Where possible separate samples have been recorded for ‘off’, standby, idle and active states.

<table>
<thead>
<tr>
<th>Appliance</th>
<th>W Ave</th>
<th>VAR Ave</th>
<th>dispPF</th>
<th>theta</th>
<th>truePF</th>
<th>THDAve</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICT_CHGR_ERIKSON_L377AQ.csv</td>
<td>4.545294</td>
<td>-0.9253</td>
<td>0.979902</td>
<td>11.50664</td>
<td>0.558549</td>
<td>144.1463</td>
</tr>
<tr>
<td>ICT_CHGR_NOKIA_SE249BB.csv</td>
<td>2.993994</td>
<td>-0.7314</td>
<td>5.866477</td>
<td>0.971434</td>
<td>13.72792</td>
<td>0.510356</td>
</tr>
<tr>
<td>ICT_CHGR_SAMSUNG_SE249BB.csv</td>
<td>4.14538</td>
<td>-1.20075</td>
<td>8.28503</td>
<td>0.960517</td>
<td>16.15413</td>
<td>0.500346</td>
</tr>
<tr>
<td>ICT_CHGR_BLACKBERRY_SE217DJ.csv</td>
<td>4.844979</td>
<td>-2.50785</td>
<td>8.14218</td>
<td>0.888081</td>
<td>27.3669</td>
<td>0.595047</td>
</tr>
<tr>
<td>ICT_LT_DELL_L377AQ_1_ACT.csv</td>
<td>62.30489</td>
<td>-17.5212</td>
<td>117.0109</td>
<td>0.962659</td>
<td>15.70691</td>
<td>0.532471</td>
</tr>
<tr>
<td>ICT_LT_DELL_L377AQ_1_IDLE.csv</td>
<td>45.63202</td>
<td>-12.8647</td>
<td>82.8865</td>
<td>0.962482</td>
<td>15.74439</td>
<td>0.555036</td>
</tr>
<tr>
<td>ICT_LT_DELL_L377AQ_1_SB.csv</td>
<td>0.406436</td>
<td>-4.78756</td>
<td>4.959995</td>
<td>0.08459</td>
<td>85.14756</td>
<td>0.081943</td>
</tr>
</tbody>
</table>

\(^{90}\) PCs that are connected to the mains but in an ‘off’ state often present a load.

CHGR = mobile phone charger.
LT = Laptop computer.

The main findings with regards to ICT appliances are as follows:

- The power consumptions of the appliances measured are consistent with the findings in chapter 3.
- Laptops are considerably lower power than desktop computers.
- Modern high performance laptops do not use more power than older models.
- Modern LCD monitors consume around half the energy of old CRT monitors.
• Printers can be the most power hungry appliances of an ICT setup, where laser technology is used.
• ICT components can generate considerable harmonic power flow.

10.2.6 Consumer

As with ICT there are too many consumer appliances to fit comfortably into a table. For details on individual appliances please see the appendix. The main findings with regards to consumer electronics are:

• In some appliance types, there is a wide range of power consumption between similar models. For example table 38 shows us there is a wide variety in both older CRT and LCD television technologies. The implication of this is that some mechanism to promote best design practices may be appropriate to reduce unnecessary waste.
• Conversely some appliances appear to have similar design norms, see table 39.
• As with ICT some products cause significant harmonic power flow.

| Table 38 Energy use of a range of old and new 26inch televisions. |
| --- | --- | --- |
| Appliance | WAve | VARAve |
| Cons_TV_CRT_26_L377AQ_ACT.csv | 79.12622 | -13.0285 |
| Cons_TV_CRT_26_SE270HP_1_ACT.csv | 57.18771 | -7.64431 |
| Cons_TV_CRT_26_SE270HP_7_ACT.csv | 126.0584 | -24.0769 |
| Cons_TV_LCD_26_L372HS_ACT.csv | 79.72545 | -13.0526 |
| Cons_TV_LCD_26_L374BD_ACT.csv | 104.274 | -20.9049 |
| Cons_TV_LCD_26_SE249BB_ACT.csv | 130.3638 | 35.75332 |

| Table 39 Energy use of a range of DVD players. |
| --- | --- | --- |
| Appliance | WAve | VARAve |
| Cons_DVD_L377AQ_ACT.csv | 10.53753 | -3.31552 |
| Cons_DVD_SE217DJ_ACT.csv | 11.03582 | -2.33983 |
| Cons_DVD_SE218JD_ACT.csv | 10.60833 | -3.81335 |
| Cons_DVD_SE249BB_2_ACT.csv | 10.75359 | -3.44948 |
| Cons_DVD_SE249BB_ACT.csv | 13.15784 | -3.56493 |
10.3 Summary of findings

The data sampled from domestic appliances has revealed a disparate collection of load patterns, magnitude and reactive power content. The switching frequencies of some appliance loads is in the order of seconds, and this supports the earlier findings that models may benefit from higher time resolution. The presence of reactive power flow, sometimes in excess of active power flow, also questions assumptions that it can be ignored in the domestic environment. The survey has also revealed some commonality aspects of appliance design. The similarity of load profiles seen with cold and cooking appliances suggests that many of the variants in use could be modelled in a similar manner, requiring only a limited number of parameters to specify different models.

Whilst washing machines present a number of varieties in terms of wash programme, again there is a great deal of commonality in other aspects of their design. Conversely, whilst consumer and ICT categories exhibit relativity simple load variation when in operation, i.e. on, idle, standby, off, there is a wide distribution of both load magnitude and phase amongst some similar appliances. Whether these temporal and phase load variations are significant is an open question which will be addressed in the following chapter.

The overall approaches to appliance design appear to be, on the whole, similar to those used before the renewed interest in energy efficiency. Analysis of wet appliances shows that efficiency gains have been made through changes in programme cycle design, particularly water use patterns, with machine hardware remaining essentially the same. The appliance labelling scheme has thus been effective in addressing this ‘latent waste’. Further reductions in energy use will require further innovation and perhaps the use of new technologies as discussed in chapter 3.

Electronic devices, now present in all categories of appliance, present high levels of harmonic power flow. CFLs, and some consumer and ICT devices show current flow that is predominantly harmonic.
Towards holistic demand side modelling

The previous chapter revealed the variety of load profiles presented by domestic appliances. The temporal and phase variation that characterises these loads has, in previous research, been obscured by the sampling methods used. Similarly, residential demand modelling has tended towards synthesising load profiles for large communities, with resolutions consistent with those used in wholesale electricity markets. This chapter explores the possibility of synthesising load profiles for individual homes and communities in a manner that preserves load amplitude and phase information.

Returning to Gelling’s definition of DSM, changes in a households demand profile can be caused by changes in end-use and through electricity output. A change in end-use refers to any change that affects a demand profile of a specific energy service including: the residential setting, building infra-structure, appliance design, appliance ownership and consumer behaviour. Electricity output refers to generation, for example solar panels, or storage within the home that can affect the net profile seen on the distribution network. If we imagine an idealised modelling system, it might allow us to experiment with all of these determining factors in a way that produces realistic data about their effects. The extent to which this is possible is limited largely by the availability of data, and in practice some data will be abundant and other data scarce.

Data is required to describe static and dynamic aspects of a model. We need data to describe the physical aspects of the network we are simulating, for example the number of homes, lengths of cables, and details about the appliances owned by households. We can call this the static model of the simulation. The static model does not in itself allow us to synthesise power flow data. For this, the static model needs to be animated in some way, which requires information about human activity and the environment. We can call this the dynamic model of the simulation design.
In simple terms, using the analogy of a model train system, the static model would represent the tracks, stations and trains, the dynamic model would be represented by the timetable.

There are a number of publicly available sources of data for both the static and dynamic model, some of which have already been discussed. The MTP data presented in chapter 3 provides estimates of the average energy per use and number of uses per annum for the most common domestic appliances. The energy use data provides us with a guide as to the relative energy consumption of different appliances pertaining to the static model. The usage statistics provide us with a guide as to the ‘proclivity’ (Capasso, W.Grattieri et al. 1994) for a particular appliance to be used and hence input for the dynamic model.

Time use surveys, (TUS) which have been used in a number of previous designs (Lampaditou and Leach 2005; Richardson, Thompson et al. 2007), provide us with a rich source of information about the day to day activities of occupants in domestic dwellings. The UK TUS survey, last conducted in 2005, also comprises static model data relating to, for example, appliance ownership, although the data set is limited.

While the TUS gives us a good understanding of how people spend their time, specific details of appliance usage is less clear. For example, while we can assume, with some certainty that, if someone is watching the television then a television will be on, with other activities the mapping is less clear. For example the activity ‘laundry’ might involve the use of a washing machine, tumble dryer or neither in the case of hand washing, sorting, hanging out and folding.

In previous approaches, these mappings have been handled in a simplistic manner with an activity triggering a certain level of demand for a certain period in order to reflect different appliance types. This approach is suitable for modelling larger populations because the differences in individual appliances and behaviour will average out. If we wish to model smaller populations at higher resolutions, then we need to mimic the variance in the way occupants behave and in the operation of individual appliances.
Previous models have simulated these variations using stochastic methods including Fourier transforms and ‘fuzzy logic'. However these approaches have been criticised for offering ‘black box’ solutions, in that while they produce realistic diurnal curves, the relationship between input parameters and real-life factors is obscure (Stokes, Rylatt et al. 2003).

This chapter proposes an approach to modelling that extends the tradition of ‘bottom up’ or engineering models. Rather than providing another demand side model, a framework is introduced that provides a platform for the development of demand side models. A key feature of the approach used is that the software is data driven, more specifically, the creation of the static and dynamic model is almost entirely determined by data files which can be modified by the user. This is the converse of ‘black-box’ approaches, since all determinants of the load profile are explicit in the input dataset.

As will be described in the following sections, an important concept in this data driven framework is the ‘factory object’. Using data provided by the user as a software ‘blue-print’, factory objects create model appliances, homes and networks. In this way the structure of the electrical network, population demographic, behavioural habits and appliance behaviour can all be modified without editing the software.

The exception to this is the behaviour of framework ‘primitives’. These are the lowest level ‘building blocks’ of the design. For example in the case of defining appliances we need a common language to define their characteristics\textsuperscript{91}.

Besides the computational limitations of modelling complex systems and the costs of data collection as discussed earlier, an additional challenge relates to the management of data. In attempting to model, for example, a network of 160 properties\textsuperscript{92} each with

\textsuperscript{91} These are described in the following section.

\textsuperscript{92} This is the typical number of homes under one substation, discussed later.
50 appliances\textsuperscript{93}, we need to build and simulate 8000 electrical components. Moreover we need to manage the activation of these appliances by modelling human interaction, as well as the effect of environmental conditions on human and appliance behaviour\textsuperscript{94}.

Previous domestic demand models have not ventured to this level of detail, but developments in the computational power and modern software development methodologies make such an approach at least theoretically possible. A common approach to modern software development is Object Orientation (OO). Object Orientation is a programming paradigm designed to aid the development of complex software systems. Using OO the engineering focus is on ‘objects’ and this encourages mapping of software components to real world objects:

‘Object orientation is a paradigm in which to frame solutions to software problems. It is a paradigm of abstraction that allows us to represent entities from the problem domain as software objects with particular states and behaviours.’

(Martin 1995)

Individual objects are generated from a software template called a Class. Classes enforce the OO approach by formally associating data and the functions (called methods in OO) to be applied to them.

Given that objects can contain references to other objects and lists of objects, highly complex systems can be developed, which, if appropriately designed, can be robust, understood by other engineers, and maintainable. For example, an OO electricity billing system might contain Classes called ‘Meter’, ‘Customer’, ‘Bill’ and ‘MeterReading’. The customer object might have a Method called ‘calculateBill’ and this would require references to the meters object associated with that customer and in turn their meter readings.

At the time of writing, there are three languages widely used for OO application development, C++, JAVA and C#. C++ is an evolution of the popular non OO

\textsuperscript{93} Here we consider lighting devices to be appliances.

\textsuperscript{94} For example when people turn lights on or when a thermostat demands heat.
language C, JAVA is a simplified platform independent OO language, and C# is a language similar to JAVA developed by Microsoft. JAVA was selected for this project because, it is operating system independent, software tools are available at no cost, the simplified Java OO model reduces temptation for unnecessary complexity and memory management is automated\(^9\). Two books were used for reference during the software development, JAVA 2 (Cadenhead and Lemay 2004), and Effective JAVA (Bloch 2001), the first providing a language reference and the later a guide to design philosophy.

The following section first describes how the framework builds the static network model object and then describes how this model is animated. The framework is then demonstrated with data sets defined to synthesise a winter weekday for profile class one, i.e. domestic consumers without electrical heating.

Using the data collected in the previous chapter, individual appliances are modelled to mimic individual appliances, rather than using averaged profiles, after Capasso et al. (Capasso, W.Grattieri et al. 1994). Rather than using fixed values for active and reactive power flow, loads are modelled as impedances which respond to supply voltage. Because appliances, for example fridges and ovens, can be affected by and themselves affect room temperature, simplistic physical modelling is used to model heat flow, after Pearce et al. (Pearce, Zahawi et al. 2001). In order to shed light upon the nature of power flow and losses on LV networks, cables are modelled, after Guttromson et al. (Guttromson, Chassin et al. 2003).

\(^9\) Errors in memory allocation are a notorious source of ‘bugs’ in languages such as C and C++.
11.1 The network model data sources

Before any simulation can commence a detailed process is conducted to produce an object that represents the static model of the network to be simulated. The components involved in this process are:

- Data banks whose data are used to individualise objects, for example household related information.
- Object banks containing unique objects, for example homes and people.
- Factories which can reproduce objects based on a data description ‘blueprints’. This approach is used where we require many objects of the same type, for example the 60 watt light bulb.

The following section now outlines the process of building a network model object. The network model builder requires sources of data describing the network and the sources of objects to populate it, namely:

- Descriptions of an adequate number of unique households including appliance ownership and occupant behaviour (Home bank in figure 44).
- Additional customisable data to specify additional household characteristics for example specific appliance types (Household data bank).
- A description of interactions with appliances depending on occupant activities (Narrative bank).
- A source of appliance objects (Appliance factory)
- A high-level description of the network structure.
Figure 44 represents the various sources of objects and data used to generate a network model object for simulation.

11.1.1 Household bank

The first source of interest is home bank, and as with the other sources it must itself be constructed prior to being available to the model constructor. Figure 45 represents the various data sources used to create the Home bank.
The Home bank generator in effect creates a pool of ‘household’ objects that can be later used to populate a network model. Crucial to this part of the framework is the Office of National Statistics Time Use Survey (TUS). Last conducted in 2005, the TUS contains a snapshot of the daily life of tens of thousand of households. This process is performed in two stages, firstly selecting households from the TUS dataset based on pre-defined rules and secondly extracting and combining individual diary data with the household population.

### 11.1.1.1 Stage 1
The selection of household datasets from the TUS is performed by the software reading each line of the dataset and comparing a number of variables with a set of filter variables to ascertain whether the row should be kept or discarded. \(^{96}\)

---

\(^{96}\) All the TUS datasets are by nature held in large files, for example the file containing tabulated diary data is nearly 150 megabytes with 496 columns of data. It is not possible to open these files using generic tools such as Microsoft Excel. The alternative is to use more substantial tools such as SPSS, to translate the data into a standard database for example Oracle, or to write bespoke software. Rather
Since there are only two data types in the TUS, ordinal and scalar, a filter definition is defined in a simple text file, customisable by the user, see table 40.

Table 40 Example household filter file.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ordinal</th>
<th>Low</th>
<th>High</th>
<th>val1</th>
<th>val2</th>
<th>val3</th>
<th>......</th>
<th>Val9</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>DiaryResponse</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td></td>
<td>......</td>
<td></td>
<td>Full day diary data</td>
</tr>
<tr>
<td>Region1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>In London</td>
</tr>
</tbody>
</table>

The ‘1’ in the ordinal column informs the framework that the filter is an ordinal type, conversely ‘0’ indicates scalar. In this example, only households from London who have a complete set of diaries are selected. The variables in question are ordinal and only rows of data that match these criteria will be selected for the final dataset.

The variable name used here is not the ONS TUS data name but an internal name used by the model. Each TUS data file used by the model has a corresponding file which defines how the data is interpreted in the model. In this case the file is ‘hhld_variables.csv’ which must be located in the same folder as the TUS datasets.

Once selected, all scalar data and ordinal data of the YES/NO variety are recorded for the household. The ordinal data refers mainly to the ownership of appliances, scalar to variables such as number of children.

11.1.1.2 Stage 2

Once a subset of households has been selected, a similar process is conducted with the individual diary data. Firstly, only individuals that are from selected households are examined. These then undergo a further filtration, allowing removal of households based on individual characteristics.

Table 41 Example diary filter file.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Ordinal</th>
<th>Low</th>
<th>High</th>
<th>val1</th>
<th>val2</th>
<th>val3</th>
<th>......</th>
<th>val9</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dday</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td>......</td>
<td></td>
<td>Weekday</td>
</tr>
<tr>
<td>Month</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td>Dec Jan Feb</td>
</tr>
</tbody>
</table>

than use a mix of software platforms it was decided that writing a data handler in JAVA would allow closer integration with other software components.

97 This abstraction allows TUS survey changes without modifying the software.
Table 41 represents the contents of a filter file that rejects households other than those with winter weekday diary datasets. Once a set of homes and associated occupants have been selected an additional process interprets the raw diary data into a ‘diary schedule’. In its raw form, diary data is supplied in 432 columns of data representing ten minute time slots of a primary activity, a secondary activity and a location. Firstly, only activities that are at location ‘home’ are selected and then primary and secondary activities analyses and converted into a more meaningful data structure. Tables 42 and 43 are real examples narratives takes from the TUS, filtered as per table 40 and 41. The two dairies are from a couple living in the same house.

Table 42 Example household occupant 1 winter weekday diary$^{98}$.  

<table>
<thead>
<tr>
<th>Start</th>
<th>Stop</th>
<th>Primary activity</th>
<th>Secondary activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>07:50:00</td>
<td>08:20:00</td>
<td>Wash and dress</td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>08:20:00</td>
<td>08:30:00</td>
<td>Caring for pets</td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>08:30:00</td>
<td>08:40:00</td>
<td>Food preparation</td>
<td>Socialising with household members</td>
</tr>
<tr>
<td>08:40:00</td>
<td>08:50:00</td>
<td></td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>08:50:00</td>
<td>09:20:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>09:20:00</td>
<td>09:30:00</td>
<td>Dish washing</td>
<td>Socialising with household members</td>
</tr>
<tr>
<td>09:30:00</td>
<td>09:40:00</td>
<td></td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>09:40:00</td>
<td>10:10:00</td>
<td>Cleaning dwelling</td>
<td></td>
</tr>
<tr>
<td>10:10:00</td>
<td>10:20:00</td>
<td>Reading periodicals</td>
<td></td>
</tr>
<tr>
<td>10:20:00</td>
<td>14:00:00</td>
<td>Food preparation</td>
<td></td>
</tr>
<tr>
<td>14:00:00</td>
<td>14:40:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>14:40:00</td>
<td>15:10:00</td>
<td>Laundry</td>
<td></td>
</tr>
<tr>
<td>15:10:00</td>
<td>15:20:00</td>
<td>Food preparation</td>
<td></td>
</tr>
<tr>
<td>15:20:00</td>
<td>15:50:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>15:50:00</td>
<td>16:00:00</td>
<td>Punctuating activity</td>
<td></td>
</tr>
<tr>
<td>16:00:00</td>
<td>16:30:00</td>
<td>Visiting and receiving visitors</td>
<td></td>
</tr>
<tr>
<td>17:30:00</td>
<td>17:40:00</td>
<td>Food preparation</td>
<td>Socialising with household members</td>
</tr>
<tr>
<td>17:40:00</td>
<td>17:50:00</td>
<td></td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>17:50:00</td>
<td>18:20:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>18:20:00</td>
<td>18:30:00</td>
<td>Dish washing</td>
<td>Socialising with household members</td>
</tr>
<tr>
<td>18:30:00</td>
<td>19:00:00</td>
<td>Dish washing</td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>19:00:00</td>
<td>19:10:00</td>
<td>Laundry</td>
<td></td>
</tr>
<tr>
<td>19:10:00</td>
<td>19:20:00</td>
<td>Ironing</td>
<td>Socialising with household members</td>
</tr>
<tr>
<td>19:20:00</td>
<td>20:10:00</td>
<td></td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>20:10:00</td>
<td>21:00:00</td>
<td>Unspecified TV watching</td>
<td></td>
</tr>
<tr>
<td>21:00:00</td>
<td>21:10:00</td>
<td>Food preparation</td>
<td>Socialising with household members</td>
</tr>
<tr>
<td>21:10:00</td>
<td>21:30:00</td>
<td></td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>21:30:00</td>
<td>22:10:00</td>
<td>Unspecified TV watching</td>
<td></td>
</tr>
</tbody>
</table>

$^{98}$ Note that the abbreviations in the table are as per the TUS and not spelling mistakes.
Table 43 Example household occupant 2 winter weekday diary

<table>
<thead>
<tr>
<th>Start</th>
<th>Stop</th>
<th>Primary activity</th>
<th>Secondary activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:20:00</td>
<td>08:40:00</td>
<td>Wash and dress</td>
<td>Adult diary - no secondary activity recorded</td>
</tr>
<tr>
<td>08:40:00</td>
<td>09:00:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>09:00:00</td>
<td>10:10:00</td>
<td>Reading periodicals</td>
<td></td>
</tr>
<tr>
<td>10:10:00</td>
<td>10:40:00</td>
<td>Gardening</td>
<td></td>
</tr>
<tr>
<td>10:40:00</td>
<td>11:00:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>13:10:00</td>
<td>13:20:00</td>
<td>Punctuating activity</td>
<td></td>
</tr>
<tr>
<td>13:20:00</td>
<td>13:30:00</td>
<td>No main activity, no idea what it might be</td>
<td></td>
</tr>
<tr>
<td>13:30:00</td>
<td>14:00:00</td>
<td>Socialising with household members</td>
<td></td>
</tr>
<tr>
<td>14:00:00</td>
<td>14:40:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>14:40:00</td>
<td>15:20:00</td>
<td>Other specified gardening and pet care</td>
<td></td>
</tr>
<tr>
<td>15:20:00</td>
<td>16:00:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>16:00:00</td>
<td>16:10:00</td>
<td>Punctuating activity</td>
<td></td>
</tr>
<tr>
<td>16:10:00</td>
<td>16:30:00</td>
<td>No main activity, some idea what it might be</td>
<td></td>
</tr>
<tr>
<td>17:30:00</td>
<td>18:00:00</td>
<td>No main activity, no idea what it might be</td>
<td></td>
</tr>
<tr>
<td>18:00:00</td>
<td>18:50:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>18:50:00</td>
<td>19:10:00</td>
<td>Dish washing</td>
<td></td>
</tr>
<tr>
<td>19:10:00</td>
<td>20:20:00</td>
<td>Other specified making, repairing and maintaining equipment</td>
<td></td>
</tr>
<tr>
<td>20:20:00</td>
<td>21:10:00</td>
<td>Unspecified TV watching</td>
<td></td>
</tr>
<tr>
<td>21:10:00</td>
<td>21:30:00</td>
<td>Eating</td>
<td></td>
</tr>
<tr>
<td>21:30:00</td>
<td>21:40:00</td>
<td>Reading books</td>
<td></td>
</tr>
<tr>
<td>21:40:00</td>
<td>21:50:00</td>
<td>Socialising with household members</td>
<td></td>
</tr>
</tbody>
</table>

The TUS uses 268 ordinal classifications to encode daily activities. These encodings are described in the TUS UK Data Archive Data Dictionary\(^{99}\).

11.1.2 Household data bank

When the network model is constructed and individual homes are drawn from the household bank, the network description contains references to additional information that either overrides or augments the data from the TUS. There are two files associated with each household:

\(^{99}\)Filename : diary_data_8_UKDA_Data_Dictionary.doc
A condensed form of this data, containing only home based activities can be found in ‘activites.csv’.
Appliance filenames descriptor: This file, which can be unique or common to multiple households, defines the specific appliance models used within this household. This allows each household to have a different set of specific appliances.

Table 44 Excerpt from an appliance filename descriptor.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>colourTV</td>
<td>Generic_CRTTV.xml</td>
</tr>
<tr>
<td>colourTV2</td>
<td>Generic_CRTTV.xml</td>
</tr>
<tr>
<td>bwTV</td>
<td>Generic_CRTTV.xml</td>
</tr>
<tr>
<td>satellite</td>
<td>Generic_SatelliteBox.xml</td>
</tr>
<tr>
<td>cable</td>
<td>Generic_CableBox.xml</td>
</tr>
<tr>
<td>terrestrial</td>
<td>Generic_TerrestrialBox.xml</td>
</tr>
<tr>
<td>video</td>
<td>Generic_VCR.xml</td>
</tr>
</tbody>
</table>

Table 44 shows an excerpt from an actual file, which in practice is comma separated table, editable in a conventional spreadsheet. The variable names on the left are those defined in the household bank build process and are common between households. The values on the right refer to user-defined or pre-defined appliance model filenames.

Household information descriptor: this file, which again can be unique or common to multiple households, allows additional attributes to be added to the household.

Table 45 TUS household data relating to appliance ownership.

<table>
<thead>
<tr>
<th>Colour TV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Second Colour TV</td>
<td></td>
</tr>
<tr>
<td>Black and white TV</td>
<td></td>
</tr>
<tr>
<td>Satellite box</td>
<td></td>
</tr>
<tr>
<td>Cable box</td>
<td></td>
</tr>
<tr>
<td>Terrestrial box</td>
<td></td>
</tr>
<tr>
<td>Video recorder</td>
<td></td>
</tr>
<tr>
<td>Freezer</td>
<td></td>
</tr>
<tr>
<td>Washing Machine</td>
<td></td>
</tr>
<tr>
<td>Tumble dryer</td>
<td></td>
</tr>
<tr>
<td>Dishwasher</td>
<td></td>
</tr>
<tr>
<td>Microwave</td>
<td></td>
</tr>
<tr>
<td>Telephone</td>
<td></td>
</tr>
<tr>
<td>Mobile</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td></td>
</tr>
<tr>
<td>Internet</td>
<td></td>
</tr>
</tbody>
</table>
Table 45 shows us a subset of ordinal data in the TUS which indicate if a household owns a particular appliance. The Household information file allows this data to be augmented on a house by house basis.

### Table 46 Excerpt from a Household information descriptor.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven</td>
<td>YES</td>
</tr>
<tr>
<td>cookerHood</td>
<td>rand() &lt; 0.18</td>
</tr>
<tr>
<td>Kettle</td>
<td>rand() &lt; 0.97</td>
</tr>
<tr>
<td>deepFatFryer</td>
<td>rand() &lt; 0.34</td>
</tr>
<tr>
<td>sandwichToaster</td>
<td>rand() &lt; 0.33</td>
</tr>
<tr>
<td>electricHob</td>
<td>rand() &lt; 0.46</td>
</tr>
<tr>
<td>Toaster</td>
<td>rand() &lt; 0.8</td>
</tr>
<tr>
<td>slowCooker</td>
<td>rand() &lt; 0.2</td>
</tr>
<tr>
<td>Fridge</td>
<td>YES</td>
</tr>
<tr>
<td>Iron</td>
<td>YES</td>
</tr>
<tr>
<td>Radio</td>
<td>YES</td>
</tr>
<tr>
<td>Hifi</td>
<td>YES</td>
</tr>
</tbody>
</table>

Table 46 show an excerpt from an actual file and here we can see that appliance ownership and other attributes can be fixed or defined stochastically, with the actual properties of the household determined at run time. For example slowCooker having a value of ‘rand() < 0.2’ means that on average 20% of houses will have a slow cooker at runtime. If the attribute of the same name exists already, that is from the TUS, then this file overrides the original value. In this way, we can for example change ownership statistics of appliance types from those in the TUS. As well as the simple stochastic expressions described above, the framework also allows more complex expressions to be used. This functionality will be demonstrated in more detail later.
11.1.3 Appliance factory

While earlier approaches to demand modelling have used simplified representations of appliances, typically using a value for wattage and duration, because we aspire to capture the dynamic characteristics of a network more accurate modelling of appliance behaviour is required.

As described in the previous chapter, appliance demand characteristics fall into a number of distinct classes. Moreover, certain appliances can exhibit a mixture of demand characteristics depending on their mode of operation. For example, washing machines comprise two dominant load categories, a simple resistive element for heating and an inductive motor. This is problematic because these two aspects of demand affect the network in different ways thus cannot be reduced to a single variable changing against time.

The approach used to tackle this aspect of the design has been to define appliances as arbitrary collections of sub components, with each component able to substitute some aspect of the appliance load characteristics. This also allows sets of sub components to be gathered in collections to mimic different setting of a machine. Because the appliance definition is now multidimensional, and because we aspire to a data driven design, a hierarchical language is required to form machine ‘blueprints’. As per the network structure described later, XML\textsuperscript{100} is well suited to such an approach.

Figure 46 presents a section of XML from a washing machine definition file. This section described one cycle with in one machine setting. Using a tree structure machines are described as collection of settings, which are collections of cycles, which are collections of parts. Whilst only one ‘setting’ can be active at one time, ‘cycles’ operate sequentially within a setting, and ‘parts’ operate concurrently within a cycle.

\textsuperscript{100}eXtensible Markup Language is a standard text based language which can be used to develop data dialects.
‘Parts’ reflect the lowest level of the model and cannot be defined by the user, but as seen in figure 46, they do have variable parameters. The example cycle shown performs two functions, it simulates a heating element’s resistive load, affecting a simple thermal model, and it simulates the agitation process of a washing machine motor by ‘replaying’ samples taken with a power analyser.

```
<cycle>
  <name>heat and agitate</name>
  <part>
    <type>Heater</type>
    <name>water heater</name>
    <container>drum</container>
    <W>2250</W>
    <VAR>0.0</VAR>
    <targetTemp>40.0</targetTemp>
    <hysterisis>0.0</hysterisis>
    <critical>YES</critical>
  </part>
  <part>
    <type>Sample</type>
    <name>agitator1</name>
    <filename>agitate_10_E.csv</filename>
    <loop>0</loop>
    <repeat>100</repeat>
    <critical>NO</critical>
  </part>
</cycle>
```

Figure 46 Excerpt from a washing machine definition.

This small excerpt demonstrates how a ‘cycle’ can contain multiple ‘parts’, with most of the variables being fairly straight forward, for example W being Watts. The ‘critical’ variable is important because it denotes which part must ‘complete’ before the cycle is over and thus the next cycle commenced. In this example, the next cycle commences when a model volume of water has reached 40 degrees centigrade. The sample mimicking the motor profile repeats up to 100 times while the heating process takes place, in practice this cycle will complete well before 100 repetitions.

The part primitives available for appliance design are as presented in table 47.
### Table 47 Appliance model primitive descriptions.

<table>
<thead>
<tr>
<th>Primitive name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>ConstantPower</td>
<td>A load that’s impedance decreases with voltage drop estimating constant power flow.</td>
</tr>
<tr>
<td>Controller</td>
<td>Allows other machines to be activated, described in more detail in a later section.</td>
</tr>
<tr>
<td>DrainPump</td>
<td>Allows draining of an appliance fluid container at fixed rate.</td>
</tr>
<tr>
<td>FillValve</td>
<td>Allows fluid vessel to be filled from external ‘tap model’.</td>
</tr>
<tr>
<td>Flame</td>
<td>Provides heat from gas.</td>
</tr>
<tr>
<td>Flush</td>
<td>Empties all the fluid from an appliance vessel.</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>Allows a fixed amount of heat energy to be transferred between fluid volumes.</td>
</tr>
<tr>
<td>HeaterElement</td>
<td>Allows variable amount of heat energy, dependant on voltage, to be removed or added to the appliances fluid volume.</td>
</tr>
<tr>
<td>LevelSensor</td>
<td>This allows volume and temperature of fluid to be monitored and acted upon.</td>
</tr>
<tr>
<td>MonitorAll</td>
<td>Part which is completed when all other parts are complete.</td>
</tr>
<tr>
<td>MonitorEnergy</td>
<td>Monitors appliances and is complete when the target appliance has used a given amount of energy.</td>
</tr>
<tr>
<td>MonitorState</td>
<td>Monitors to see if a machine is in the complete state.</td>
</tr>
<tr>
<td>PulsedCoolingFan</td>
<td>Allows fluid flow between containers.</td>
</tr>
<tr>
<td>PulsedHeatExchanger</td>
<td>Allows heat exchange between containers.</td>
</tr>
<tr>
<td>PulsedJ</td>
<td>Allows simplified modelling of pulse width modulated loads for example cooker elements. On cycle width is determined by energy delivered.</td>
</tr>
<tr>
<td>PulsedZ</td>
<td>Allows simplified modelling of pulse width modulated loads for example cooker elements. On cycle is determined in seconds.</td>
</tr>
<tr>
<td>RemoteSwitch</td>
<td>Allows machines to wait for external signals.</td>
</tr>
<tr>
<td>Sample Player</td>
<td>Allows ‘replay’ of complex load patterns such as those involving motors.</td>
</tr>
<tr>
<td>TimeSwitch</td>
<td>Waits for a specific time of day.</td>
</tr>
<tr>
<td>Timer</td>
<td>Allows pauses between and hold function for loads.</td>
</tr>
<tr>
<td>Z</td>
<td>Complex impedance.</td>
</tr>
</tbody>
</table>

Before any appliance can be built by the factory, any sample data referenced in the XML templates must already be available to the builder. This is performed automatically by the Sample Bank Generator provided that the samples are available in a subdirectory to the appliance files. To allow the use of raw data taken from a power analyser, data input can be rescaled depending on the test equipment used. Figure 47 represents the key components used to instantiate appliance model objects.
The scaling factors and column names of the input files are defined in the file ‘config.csv’ allowing sample data from disparate sources to be used.

11.1.4 Narrative bank

The notion of *narratives* is used to describe the rules of translation from diary entries into the activation of appliance models. For example the data entry ‘cooking’ in the
TUS is abstract in that it does not describe any specific detail of what is actually taking place. If we are to simulate the energy use of ‘cooking’ we need to activate a range of appliances and lights in a realistic\textsuperscript{102} manner but differently for each home. Each household object in the model contains its own narrative builder object which uses a rule set that is shared by the rest of the household. The detail of what actions to perform are held in a ‘native definition file’, which can be unique or common to different households and these rule sets are loaded before model build time in a similar manner to the appliance factory.

Figure 48 represents the simple construction of the Narrative bank. Providing the data supplied in the narratives file is well formed, then it is simply stored in tables which can be indexed as required by filename. Details of what information is contained in a narrative rule set are described later when we explore the execution of the network model object.

\textsuperscript{102} The notion of ‘realistic’ behaviour will be explored further when runtime behaviour of the model is discussed.
11.2 Construction of the network model object

Once the various object banks, data banks and object factories have been built and loaded, the process of constructing a network model object can commence. This process will only be successful if all the references in the model have corresponding available datasets. If any reference to a household dataset, an appliance, or narrative is absent then the model construction will fail, usually resulting in an error report to allow identification of the faulty reference.

The key to what is actually simulated at runtime depends on the network model descriptor, an example of which can be seen in its entirety in figure 49. This simple example describes the following network topology.

```
Three-phase transformer
  ↓
One three-phase feeder
  ↓
One three-phase cable
  ↓
One single-phase spur connected to one phase
  ↓
One house
```

For the transformer\(^{103}\) and cables, the only attributes required are the complex impedance values for the lives and neutrals. The house has additional attributes relating to the data driven approach which has already been mentioned, namely:

- `<homeInformation>homeInformation.csv</homeInformation>`

  This attribute defines which list of additional home attributes to use.\(^{104}\)

\(^{103}\) In the current model the dynamics of transformers are not modelled and are simply represented as a ‘stiff’ fixed voltage power source.

\(^{104}\) The suffixes of ‘.csv’ are maintained to express the fact that labels all refer to real filenames that must exist in directories selected at runtime.
• `<applianceFileNames>applianceFilenames.csv</applianceFileNames>`
  This attribute defines which list of appliance models to use.

• `<narativeFilename>narative.csv</narativeFilename>`
  This attribute is used to reference the narrative rule set for this house.

```xml
<?xml version="1.0"?>
<connection>
  <type>3Ptransformer</type>
  <name>Top node</name>
  <R>0.0</R>
  <jX>0.0</jX>
  <Rneutral>0.0</Rneutral>
  <jXneutral>0.0</jXneutral>
  <connection>
    <type>3Pfeeder</type>
    <name>feeder1</name>
    <R>1.0</R>
    <jX>0.1</jX>
    <Rneutral>0.0</Rneutral>
    <jXneutral>0.0</jXneutral>
    <connection>
      <type>3Pcable</type>
      <name>feeder section</name>
      <R>0.0</R>
      <jX>0.0</jX>
      <Rneutral>0.0</Rneutral>
      <jXneutral>0.0</jXneutral>
      <connection>
        <type>1Pspur</type>
        <name>Street house link</name>
        <phase>1</phase>
        <R>0.0</R>
        <jX>0.0</jX>
        <connection>
          <type>house</type>
          <name>1</name>
          <R>0.0</R>
          <jX>0.0</jX>
      </connection>
    </connection>
  </connection>
</connection>
</connection>
</connection>
</connection>

<homeInformation>homeInformation.csv</homeInformation>
<applianceFileNames>appliance.csv</applianceFileNames>
<narativeFilename>narative.csv</narativeFilename>
</connection>
</connection>

Figure 49 Example network scenario description (tabulation adjusted to fit page).
The model object is created by the framework iteratively traversing the XML tree, producing network objects at each node and in turn adding children components to them. With most objects at this level being just cable, they are simple Java objects to construct. The most complexity is seen in the creation of the household objects.

### 11.2.1 The creation of household objects

The model builder adds an individual home to the network model in the following steps.

- A single pseudo-random household is taken from the household bank. This unique object is added to the network structure and all references deleted from the household bank to avoid duplicate use.
- The homes attribute set is augmented with additional data identified by the `<homeInformation>` variable. With this reference the home object creates its own version of these data, replacing probabilities with YES/NO attributes (for example to flag the ownership of a new appliance)
- The homes appliance filenames list is set from the home information bank with the `<applianceFileNames>` variable.
- The narrative list name is set using `<narrativeFilename>`.
- The home’s method “plugInAllAppliances” is called and this runs through the appliance ownership and filename list. It calls the appliance factory for the relevant appliance object to be created. Each appliance object is in turn connected to the wider network model and to internal objects representing, for example, water supply.

As the appliances are added to the house, the house in effect becomes a branch in the network with the appliance’s individual parts becoming the new network leaves.

---

105 All children components, unless they are leaves, are assumed to be network branches. The exception for this is `3Pfeeder`, which assumes all its children and to be organized serially. This peculiarity is simply to avoid excessive nesting in the XML and therefore excessive tabulation.
### 11.3 Network simulation

Figure 50 represents the basic structure of the framework once the network model object has been built. The network model provides a set of methods for simulation of the model and retrieval of network data.

![Figure 50 Overview of framework in simulation.](image)

Environment variables are required by the model, for example ambient temperature and sunlight, and these must be supplied in a table format before runtime.

In order to simulate the network behaviour the scenario engine must coordinate the state of the environment, homes, occupants, appliances and cabling. The simulation performs this array of tasks by breaking down each iteration of the model into separate sub tasks. These tasks are now introduced in order of execution.

The prefix of superNode on method calls indicates the internal name of the object being called to run the methods. In this implementation superNode refers to a dummy three phase connection which represents the very top or trunk of our modelled system. Thus any power flow data collected from this point represents the aggregate demand for the whole subsystem.
11.3.1 Model animation

All objects which represent a part of the physical system have a *tick* method, which progresses time by one second. Like other methods *tick* starts at the trunk of the network and progressively calls all sub branches until they are exhausted.

The most important effects of tick are seen in occupants and appliances:

11.3.1.1 Occupant activity

Upon *tick*, each occupant’s diary is interrogated, one entry in advance, to establish if there is any new diary entry pending, i.e. any new change in activity. If a new diary entry is pending, it is despatched to the individual’s *narrative* builder which creates one or more appliance interaction events which are queued in the individual’s *event schedule*. 
Figure 51 A representation of the home object and its members.

Figure 51 represents the home object model; the number of occupants is variable as is the number of associated appliances. We have previously looked at the data stored in the *diary* object, that is, a list of start and stop times for primary and secondary activities. An excerpt from a more complete narrative rule set is shown in table 48.
Table 48 Example excerpt from a narrative list.

<table>
<thead>
<tr>
<th>Start</th>
<th>Stop</th>
<th>Activity</th>
<th>Rule</th>
<th>Action</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>04:00:00</td>
<td>23:59:59</td>
<td>Laundry</td>
<td>light &lt; 50.0</td>
<td>light_kitchen</td>
<td>on</td>
</tr>
<tr>
<td>04:00:00</td>
<td>23:59:59</td>
<td>Laundry</td>
<td>rnd &lt; 0.5</td>
<td>Tumbledryer</td>
<td>on</td>
</tr>
<tr>
<td>04:00:00</td>
<td>23:59:59</td>
<td>Laundry</td>
<td>rnd &gt; 0.25</td>
<td>washingmachine</td>
<td>cotton 40</td>
</tr>
<tr>
<td>04:00:00</td>
<td>23:59:59</td>
<td>Ironing</td>
<td>light &lt; 50.0</td>
<td>light_kitchen</td>
<td>on</td>
</tr>
<tr>
<td>04:00:00</td>
<td>23:59:59</td>
<td>Ironing</td>
<td>1</td>
<td>Iron</td>
<td>cotton</td>
</tr>
<tr>
<td>04:00:00</td>
<td>17:00:00</td>
<td>Eating</td>
<td>light &lt; 50.0</td>
<td>light_kitchen</td>
<td>on</td>
</tr>
<tr>
<td>17:00:00</td>
<td>23:59:59</td>
<td>Eating</td>
<td>light &lt; 50.0</td>
<td>light_dining</td>
<td>on</td>
</tr>
<tr>
<td>04:00:00</td>
<td>23:59:59</td>
<td>Eating</td>
<td>1</td>
<td>Fridge</td>
<td>open</td>
</tr>
</tbody>
</table>

Start and stop provide time windowing in order that we can, for example, distinguish between breakfast, lunch and dinner.

Activity is the diary activity which must exactly match the internal TUS label in order to trigger the action\textsuperscript{106}.

Rule is a mathematical expression which must return true in order for the Action to be triggered. The rule can use any expression which results in a Boolean result. Input variables include all the homes and individuals parameters as well as global variables light (light level outside), temp (ambient temperature) and rnd, a random value between 0 and 1 generated for each call to the narrative builder (i.e. not for each rule).

Setting is required to distinguish between different machine settings, for example cotton 40 on the washing machine. Simple appliances, such as the light bulb, have just two settings, on and off, and in these cases they are simply activated for the duration of the activity. Other more complex appliances must complete a fixed process that are rarely interrupted, for example washing machines. The specific behaviour of different machine categories is covered in the following section.

\textsuperscript{106} This is important to note because all activity names can in effect be user defined so attention must be paid to spelling consistency.
11.3.1.2 Machine activity
All appliances owned by a household are represented by a machine object. Like the occupant objects, machines have a *tick* method which is called with every cycle of simulation.

![Machine object hierarchy diagram]

Figure 52 Representation of machine object hierarchy.

At any given time a machine is represented as a complex impedance. This impedance is calculated from the parallel sum of all the constituent parts of a given cycle, described in the next section. The *tick* function of a machine does not calculate the parallel impedance but manages what state the machine is in. It will change *cycle* if the current *critical part* is complete, otherwise, unless interrupted, the machine remains in the same cycle. If a final cycle is completed then the *setting* is complete and the machine falls back into the machines *standby* or *off* setting.\(^\text{107}\)

\(^{107}\) All machines must have an off and/or standby setting defined in their XML definition.
11.3.1.3 Mimicking complex human activities

The preceding description of occupant and appliance interactions used simple example narrative rules with one to one, or one to many relationships. For example if the occupant is performing laundry, there is a chance that they activate the washing machine and/or the tumble dryer, and turn on the kitchen or utility room light if it is dark. Even a simplistic approach like this can lead to quite complex elaboration of actual appliance activations; however it is limited in that it does not allow a sequence of events to stem from a single diary entry.

Some diary activities lend themselves to a simplistic interpretation of habit, such as watching television as mentioned earlier. Other activities such as ‘cooking’ might take on a multitude of forms, with different appliances, on different settings at different times. In this aspect of the design we can benefit from social norms, or what might be described, in electrical terminology as a lack of diversity. In other words, whilst many variations are possible, people actually tend to eat very similar things and cook their meals in similar ways. For example there are few ways to cook a micro-wave meal, and roast dinners typically involve an oven and couple of hobs. Give that we are not trying to mimic actual events, but realistic events we can prescribe methods for different meal types providing there is enough diversity to avoid obvious duplication of activities amongst neighbours. Whilst this approach would benefit from a thorough survey of cooking habits, this is to some extent mitigated by the fact that electric cookers are simple loads, in other words what ever is cooking, the cooker presents a similar load profile. If we refer back to Jackson’s analysis (Jackson 2005), that much of our behaviour is encoded in habits, and these are performed ‘automatically’, then we can consider occupants habits as representing a form of mechanisation.

Extending this notion to the framework design, as described earlier complex procedures are already possible using the machine object, with its hierarchy of settings, cycles and parts. Rather than invent a new XML dialect for describing complex human behaviour, the machine class is extended to allow control of other machines. This capability allows a machine to control another machine in the same way as an occupant. A further extension allows a part to sense if a setting is complete and how much energy a machine is using.
Using this approach it is possible to break down behaviour into a hierarchy of habits, where, for example, the narrative engine identifies ‘spaghetti bolognaise’ as the meal to be cooked and a habit ‘robot’ mimics the management of the necessary appliances. This extension to the machine class also allows us to design thermostats and other autonomous control equipment including testing procedures for software validation.

Figure 53 shows an example of washing and dressing habits, where a shower is followed by hair drying, a common activity for women. Since different individuals will shower for different period, likewise dry hair, these processes are defined in sub habits, which in turn activate a given appliance. This use of abstraction allows us to create many variants of behaviour by providing different sub habits for different homes at run time. In this case the variation in the sub habits is the duration of the shower and hair drying time.
Figure 53 Excerpt from a ‘bathroom habit’ definition.
11.3.2 Calculating power flow

In the preceding sections, the notion of a hierarchical object model representing the system has been introduced. The focus on the data driven approach has been to elaborate the model sufficiently to mimic the diversity of electricity use for a given population. Despite the complex procedures in building the system model the runtime behaviour of the model is fairly straightforward.

Once household occupants and appliances are animated, as described in the previous sections, the power flow calculations are processed in four stages:

- All live impedances are calculated;
- Using the above live power flow is calculated;
- Neutral power flow is calculated;
- Neutral voltages are calculated.

Each method performing these functions is described below.

11.3.2.1 superNode.propogateAllImpedance();
Since the systems to be modelled are limited to those with radial network structures, the power flow calculations used are relatively straightforward. Figure 54 provides a simple example network to demonstrate the approach used. The primary focus of the design is complex impedance, as unlike previous bottom up approaches the effects of cable impedance are to be examined.
Assuming Z1 is connected to a stable 250V supply, Z1 can represent a single phase spur from a street. Z2 represents the internal impedance of the house’s cabling. Z3 through Z6 represent the active parts in two appliances. The machine parts are nested within a setting and cycle, but these objects are not represented since they have no inherent impedance and are not in themselves part of the electrical network.
Because the machine impedances can change on a second to second basis, the network impedance is recalculated every second. Each node in the network, that is any cable, home, or appliance part, has two internal complex variables:

**Zdemand**  Represents the sum complex impedance of all its children objects. In the case of the home this would be the sum of Z3, Z4 Z5, Z6 in parallel.

**Zload**  Is Zdemand plus any internal impedance, i.e. the load seen by the parent node. In this home this would be sum of Z3, Z4 Z5, Z6 in parallel plus Z2 in series.

These values are calculated by traversing the network tree backwards, from leaf to trunk, since it is the leaves or appliances that change. Once complete, each node on the network has a value of the impedance seem below it and the impedance it presents to its parent. The only complex mathematics involved here was the summing of parallel impedances, the equations for this were copied from an internet educational resource ‘hyperphysics’ (Nave 2009).

11.3.2.2  `superNode.propogateAllPower();`

With the values for Zdemand and Zload (complex impedances) established, for a given source voltage at 50Hz we can calculate the real and imaginary power flows at each point in the network.

This stage of the process could be performed in a multitude of ways. For example an external programme or ‘solver’ could be fed network description (Zimmerman, Murillo-Sánchez et al. 2007), alternatively libraries could linked at runtime (Flanagan 2009) or bespoke software designed. Each of these approaches itself could be performed in a number of ways.

The approach used here is a bespoke solution using an approximate power flow calculation taken from engineering text books (Gonen 1986). This approach was taken primarily to avoid the runtime overhead of communicating a new network structure to an external process every simulation cycle. Secondly no appropriate runtime libraries were found that could be linked at runtime.
Throughout the model, three phase systems are, on the whole, modelled as 3 single phases. However, special attention is required with neutral current flow since it is the sum of three live currents with phase shift, and this current flow contributes to losses.

There is a 120 degree phase separation of voltage on each phase of a UK three phase system. If a system is loaded equally on all three phases then the current flow cancels out, removing any current flow and consequent heating losses on the neutral. Although a system is almost never entirely in balance, this phenomena does allow for reductions in cable capacity and thus costs (Smiles 2008).

As well as the fixed 120 degrees, the relative phase angle of the current flow, i.e. reactive power, must be considered to determine the current flow in the cable. The sum of the three phases is calculated re-using the current flow vectors from the earlier live calculations rotated 120 and 240 degrees on phases 2 and 3 respectively. The residual current is then propagated back through the network and summed with other nodes.

Once the residual current flows on the neutrals are estimated, an approximation of the neutral voltage can be made. It is common for neutral to be earthed at various points in the network, primarily as a safety feature (ibid), however the model assumes that there are no earth points beyond the root component, i.e. the local transformer. Earth points typically have a resistance in the order of 20 ohms which is considerably higher than the typical cable impedances seen on a LV network, thus the omission of the earth points should not be overly significant.

As with the live cables each node has an impedance and this causes a voltage differential with current flow. The voltage of any neutral node is calculated by summing the voltage seen across the node with the voltage at the seen at the parent node.
11.3.3 Shortcomings of described approach

The approach described above, provides an approximate load flow for a dynamic model on a second by second basis. Whilst high-resolution compared to other ‘bottom up’ efforts, it is by no means exhaustive in terms of modelling actual energy flows on a network.

If our area of interest was supply quality, then much shorter transients might be of interest. Transients seen on a domestic circuit can be considerable, while lasting less than a single cycle they can be many times the average current of the appliance.

As described in the previous chapter, the current flow in many components is non-sinusoidal, in other words, it contains harmonic frequencies. Harmonic power flow causes increased losses and voltage waveform distortion which can interfere with equipment performance, thus ideally these effects could be incorporated into any simulation. However, harmonics power flows are problematic to model when compared with a DC or single frequency systems. Current harmonics are typically described in relation to the current fundamental, which can have a phase shift if reactive, and each harmonic can have a phase shift from this fundamental. To calculate harmonic current flow in the model described would require multiple phase shift calculations for each harmonic at each node of the model. Moreover, harmonics are localised, and taking the ‘path of least resistance’ current will flow in different directions in the network.

Ideally harmonics should be compensated for locally, and only the residual sinusoid is seen by the wider network. Otherwise residual harmonics propagate and mix in the system until filtered out by the passive filtering of the wider system.

Current flow on the neutral allows us to understand the approximate proportion of losses on the neutral and monitor voltage rises on the neutral. However in this model the voltage rises do not result in changing the power flows on the lives, as they would in reality. This effect could be estimated by iterating the current flow and voltage calculations, up and down the network, performing successive approximations. Whilst this might present an opportunity for a future improvement to the model, it was not pursued on grounds of execution speeds.
In summary this approach to modelling power flow has the following shortcomings:

- Loss of sub-second transient information.
- Harmonic power flow effects ignored.
- Neutral voltage rise ignored in live current flow calculations.
11.4 User Interface

The framework presented requires a number of data sources to be indentified before each simulation can be executed. To simplify this process a graphical user interface (GUI) allows users to select a range of parameter sets. Some files are identified directly and some indirectly by providing the GUI with a collection of folders where the necessary data can be found. For example the filenames of home information and appliances filename lists are stored in the XML network description, however the GUI allows these source to be taken from different folders. In this way, for example, a collection of different source folders can be defined for the appliance factory machine descriptions, or for example the home information tables.

Upon execution the GUI then iteratively rebuilds a model and executes the model with the different data sources. This allows many simulation variants to be built and executed sequentially thus saving time and allowing batch simulations to be defined. Figure 55 shows the parameter input GUI pane.

Figure 55 Framework GUI parameter input selection pane.
Once a parameter set, or a collection of parameter sets is defined, then the simulation of can commence. The ‘Start Simulations’ button then initiates the process as described in the earlier sections.

The network simulation pane as seen in figure 56 provides real-time diagnostic information as to the behaviour of the model in question. This might include, for example error information or details about simulation activity. The clock in the bottom righthand corner of the pane displays the time of day in the model being executed.

![Figure 56 FrameworkGUI network simulator pane.](image-url)
11.5 Case studies

The simulation framework introduced in the preceding sections provides a means to synthesise demand profiles for different networks, communities, and technology scenarios. If we adopt a testing strategy whereby we vary one aspect of a system at a time, ‘all other things being equal’, then we can establish what factors may or may not affect system efficiency.

Given the data driven approach, the selection of data and the consideration of appropriate assumptions is critical to the modelling process. The specific aspects of a system that we are testing also determine the relative importance of accuracy for different datasets. For example if we are not primarily concerned with household space heating efficiency, then we need not pay special attention to the accuracy of ambient temperature data. Thus whilst a data driven approach to modelling does dictate a higher level of data acquisition, assumptions can be made, and these are made explicit.

Although the framework introduced can be used to experiment with network configuration and micro-generation, as a starting point, the initial studies all pertain to changes in end use. Because the variable components are the appliances, it is necessary to fix the other aspects of the model. The following sections describe the common scenario assumptions and this is followed by a description of the approaches taken to model the appliance population.

11.5.1 Household population selection

The framework described allows the selection of households based on any attributes that are present in the time use survey data. For example, we might choose to model households from one region such as London, if we believe that location is a determinant of energy usage patterns. Conversely, it is desirable to have a large sample population to avoid introducing statistical errors. Given that location within a country is not thought to be a significant determinant of time use behaviour (Stokes,
Rylatt et al. 2003), a simple search criteria was defined that selects any household with a complete or near complete set of diary data, irrespective of location.

Filter filename: hhlds_complete_diaries.csv

### 11.5.2 Occupant diary selection

Once a set of households are selected, a subset are chosen based on the contents of occupant diary datasets. The selection could use a range criteria offered by the diary datasets, for example ethnicity or income.

Again a simple criterion is used, selecting diaries only by chronology. Because the diurnal demand curve varies seasonally and during different days of the week, datasets were selected based on season and weekday, namely winter weekdays. This allows us to select time use data that concurs with those represented by the profile classes as described earlier and provides a means to check the load shape produced by the model. Winter weekdays are interesting because this is when domestic demand is high and concurrent with commercial and industrial loads.

Filter filename: diary_winter_weekday.csv

### 11.5.3 Household data

The TUS survey contains a number of ordinal variables that indicate whether or not a household contains certain appliances or services. These data are augmented using the file ‘homeInformation.csv’. Household data pertain to both the static and dynamic aspects of the model. Appliance ownership flags pertain to the static model, flags relating to habits pertain to the dynamic model.

These data are too large to fit comfortably into one table, so are summarised with excerpts below.
11.5.3.1 Lights

Lighting loads, despite being straightforward to define in terms of their electrical characteristics, present a particular challenge in the defining ownership and usage patterns. Any room can have multiple light fittings, these can have a number of bulbs, and lights can be used alone or in combination. Market Transformation data does not provide any detail on these issues. However in 2007 the Lighting Association conducted an extensive survey of fittings and bulbs used in UK homes. The published report comprised data on the total number of fittings and bulbs, per room on a national basis. In practice it proved difficult to use these national level totals to produce likely distributions of fitting and bulbs per room, because house level detail was lost. Late in the project development, the company Tangible Solutions, under direction of the Lighting Association conducted a special data analysis specifically for the purposes of this project.

The resulting dataset comprised a room by room, fitting by fitting description of number of bulbs, bulb type and wattage for over 2000 homes. Because of the richness of this dataset, an additional software component was developed to import this data. A button was added to the framework user interface to allow the option of automatically extraction of the lighting data. With this late addition to the model, ‘home information’ now comprised data from three sources, the TUS survey, the LA ‘lighting map’ and the home information files.

Lighting use can be divided into two logical categories, functional lighting, that is light used when needed for a specific activity, and mood or ambient lighting. No survey information was found that gave any detail regarding the use of mood lighting. Thus for the dynamic modelling of lighting, a simple stochastic approach has been taken. Table 49 shows mood lighting variables. Because we don’t know in advance how many fittings a room has, here we assume that the room has up to four. Each of these new variables has a probability of 50% of being true, and indicates whether the fitting in question is part of the ‘mood lighting’ set. In themselves these variables do

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108 The Lighting Association kindly provided these data free of charge.

109 Many thanks to Sean Chamberlain of Tangible Solutions and Peter Hunt of the Lighting Association.
not define which bulbs are switched on or off, rather they are used as inputs to the narrative rules, described later.

<table>
<thead>
<tr>
<th>Mood lighting</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>mood_diningroom_1</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_diningroom_2</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_diningroom_3</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_diningroom_4</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_hall_1</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_hall_2</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_hall_3</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_hall_4</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_kitchen_1</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_kitchen_2</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_kitchen_3</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_kitchen_4</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_kitchendiner_1</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_kitchendiner_2</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_kitchendiner_3</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_kitchendiner_4</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_landing_1</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_landing_2</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_landing_3</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_landing_4</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_lounge_1</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_lounge_2</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_lounge_3</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_lounge_4</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_loungediner_1</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_loungediner_2</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_loungediner_3</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_loungediner_4</td>
<td>rand () &lt; 0.5</td>
</tr>
<tr>
<td>mood_porch_1</td>
<td>rand () &lt; 0.5</td>
</tr>
</tbody>
</table>

11.5.3.2 Cooking

The ownership of cooking appliances is defined as per the information gathered in chapter 3, which is largely as reported by the MTP. Because each hob ring on a cooker is in effect a separate machine it is useful to treat them as such in the model. However all hobs must be of the same type, since gas and electric hobs are typically not mixed. To this end we can see that table 50 uses a special feature of the framework. A variable, in this case electricHob is automatically set by the model and reused 3 times to select or deselect all the hobs. No hob result is assumed to be a gas
and not modelled, however we want to model the power supply to a gas hob thus hobSB, meaning standby is always true\textsuperscript{110}.

<table>
<thead>
<tr>
<th>Cooking</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>coffeemachine</td>
<td>rand () &lt; 0.25</td>
</tr>
<tr>
<td>cookerhood</td>
<td>rand () &lt; 0.18</td>
</tr>
<tr>
<td>deepfatfryer</td>
<td>rand () &lt; 0.34</td>
</tr>
<tr>
<td>electricHob</td>
<td>rand () &lt; 0.46</td>
</tr>
<tr>
<td>habit_bacon</td>
<td>YES</td>
</tr>
<tr>
<td>habit_bakedbeans</td>
<td>YES</td>
</tr>
<tr>
<td>habit_bakedpotatoes</td>
<td>YES</td>
</tr>
<tr>
<td>habit_bolognese</td>
<td>YES</td>
</tr>
<tr>
<td>habit_chicken</td>
<td>YES</td>
</tr>
<tr>
<td>habit_coissant</td>
<td>YES</td>
</tr>
<tr>
<td>habit_curry</td>
<td>YES</td>
</tr>
<tr>
<td>habit_egg</td>
<td>YES</td>
</tr>
<tr>
<td>habit_fishfingersandchips</td>
<td>YES</td>
</tr>
<tr>
<td>habit_freshveg</td>
<td>YES</td>
</tr>
<tr>
<td>habit_frozenreadymeal</td>
<td>YES</td>
</tr>
<tr>
<td>habit_frozenveg</td>
<td>YES</td>
</tr>
<tr>
<td>habit_hairdryer</td>
<td>YES</td>
</tr>
<tr>
<td>habit_indianreadymeal</td>
<td>YES</td>
</tr>
<tr>
<td>habit_lasagne</td>
<td>YES</td>
</tr>
<tr>
<td>habit_milk</td>
<td>YES</td>
</tr>
<tr>
<td>habit_pasta</td>
<td>YES</td>
</tr>
<tr>
<td>habit_pizza</td>
<td>YES</td>
</tr>
<tr>
<td>habit_porridge</td>
<td>YES</td>
</tr>
<tr>
<td>habit_potatoes</td>
<td>YES</td>
</tr>
<tr>
<td>habit_rice</td>
<td>YES</td>
</tr>
<tr>
<td>habit_salmonfillet</td>
<td>YES</td>
</tr>
<tr>
<td>habit_shower</td>
<td>YES</td>
</tr>
<tr>
<td>habit_stirfry</td>
<td>YES</td>
</tr>
<tr>
<td>habit_toast</td>
<td>YES</td>
</tr>
<tr>
<td>habit_vacuum</td>
<td>YES</td>
</tr>
<tr>
<td>hob1</td>
<td>electricHob</td>
</tr>
<tr>
<td>hob2</td>
<td>electricHob</td>
</tr>
<tr>
<td>hob3</td>
<td>electricHob</td>
</tr>
<tr>
<td>hob4</td>
<td>electricHob</td>
</tr>
<tr>
<td>hobSB</td>
<td>YES</td>
</tr>
<tr>
<td>Kettle</td>
<td>rand () &lt; 0.97</td>
</tr>
<tr>
<td>Kitchen_habit_cookfor1</td>
<td>YES</td>
</tr>
<tr>
<td>Kitchen_habit_cookfor2</td>
<td>YES</td>
</tr>
<tr>
<td>Kitchen_habit_cookfor4</td>
<td>YES</td>
</tr>
<tr>
<td>Oven</td>
<td>rand () &lt; 0.59</td>
</tr>
<tr>
<td>ovenSB</td>
<td>YES</td>
</tr>
<tr>
<td>Sandwichtoaster</td>
<td>rand () &lt; 0.33</td>
</tr>
<tr>
<td>Slowcooker</td>
<td>rand () &lt; 0.2</td>
</tr>
<tr>
<td>Toaster</td>
<td>rand () &lt; 0.8</td>
</tr>
</tbody>
</table>

\textsuperscript{110} It is important to remember that these variables do not dictate energy use, thus in this example power flow may be zero.

It is important to remember that these variables do not dictate energy use, thus in this example power flow may be zero.

255
To reflect a realistic diversity of appliance usage a number of cooking habit types are defined. These variables were based mainly on data available in the MTP report that compared the energy demand of different methods of cooking (MTP 2008). This dataset means that all households can cook all of the below meals, but their methods will differ depending on the details of habit. Each of the above habits has one or more associated ‘machine’ definition, which can be found in the appendix.

11.5.3.3 Cold
With regards to cold appliance ownership, the datasets from the MTP do not provide us with enough information to populate a model on a house by house basis. The main issue is that no data is provided that describes the propensity for homes to own multiple appliances. The most detailed study found on this subject was conducted by Mansouir et al. (Mansouri, Newborough et al. 1996). Table 51 shows how these data are used in framework. First 11 categories of cold appliance ownership are defined by C1-C11 reflecting the Mansouri et al. data. These categories are then used to define whether or not an appliance type is owned\(^{111}\). Separate standby power variables are defined to allow for the possible addition of individual standby load for these appliances.

<table>
<thead>
<tr>
<th>Table 51 Cold appliance flags derived from Mansouir et al.</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
</tr>
<tr>
<td>C2</td>
</tr>
<tr>
<td>C3</td>
</tr>
<tr>
<td>C4</td>
</tr>
<tr>
<td>C5</td>
</tr>
<tr>
<td>C6</td>
</tr>
<tr>
<td>C7</td>
</tr>
<tr>
<td>C8</td>
</tr>
<tr>
<td>C9</td>
</tr>
<tr>
<td>C10</td>
</tr>
<tr>
<td>C11</td>
</tr>
<tr>
<td>Freezer</td>
</tr>
<tr>
<td>freezer2</td>
</tr>
<tr>
<td>freezer2SB</td>
</tr>
<tr>
<td>freezerSB</td>
</tr>
<tr>
<td>Fridge</td>
</tr>
</tbody>
</table>

\(^{111}\) For the non software literate reader, the symbols ‘\(\|\)’ and ‘\(\&\&\)’ are the logical expressions OR and AND respectively. Thus in the case of freezer2 this will be true if C9 OR C11 are true.
11.5.3.4 Consumer
Consumer ownership is shown in table 52 and is consistent with the data presented in chapter 3. Note that TVs and other appliances are defined in the TUS dataset and do not need to be defined unless they are to be overridden. The flag satcab is an aggregated variable that flags whether we have a satellite or cable receiver, since it is uncommon to have both. Other flags are based on the author’s estimates.

<table>
<thead>
<tr>
<th>Consumer</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>dvd</td>
<td>rand () &lt; 0.78</td>
</tr>
<tr>
<td>dvd2</td>
<td>(colourTV2) &amp;&amp; (dvd)</td>
</tr>
<tr>
<td>gamesconsole</td>
<td>0.25</td>
</tr>
<tr>
<td>hifi</td>
<td>rand () &lt; 0.94</td>
</tr>
<tr>
<td>hifi2</td>
<td>(hifi) &amp;&amp; ((adults + Children8to15) &gt; 1) &amp;&amp; (rand() &lt; 0.5)</td>
</tr>
<tr>
<td>hifi2</td>
<td>(hifi) &amp;&amp; ((adults + Children8to15) &gt; 1) &amp;&amp; (rand() &gt; 0.5)</td>
</tr>
<tr>
<td>hifi3</td>
<td>(hifi2) &amp;&amp; ((adults + Children8to15) &gt; 2) &amp;&amp; (rand() &lt; 0.5)</td>
</tr>
<tr>
<td>hifi3</td>
<td>(hifi2) &amp;&amp; ((adults + Children8to15) &gt; 2) &amp;&amp; (rand() &gt; 0.5)</td>
</tr>
<tr>
<td>hifi4</td>
<td>(hifi3) &amp;&amp; ((adults + Children8to15) &gt; 3) &amp;&amp; (rand() &lt; 0.5)</td>
</tr>
<tr>
<td>hifi4</td>
<td>(hifi3) &amp;&amp; ((adults + Children8to15) &gt; 3) &amp;&amp; (rand() &gt; 0.5)</td>
</tr>
<tr>
<td>radio</td>
<td>rand () &lt; 0.95</td>
</tr>
<tr>
<td>radio2</td>
<td>(radio) &amp;&amp; ((adults + Children8to15) &gt; 1)</td>
</tr>
<tr>
<td>radio3</td>
<td>(radio2) &amp;&amp; ((adults + Children8to15) &gt; 2) &amp;&amp; (rand() &lt; 0.5)</td>
</tr>
<tr>
<td>radio4</td>
<td>(radio3) &amp;&amp; ((adults + Children8to15) &gt; 3) &amp;&amp; (rand() &lt; 0.5)</td>
</tr>
<tr>
<td>satcab</td>
<td>rand () &lt; 0.526</td>
</tr>
<tr>
<td>satcab2</td>
<td>(colourTV2) &amp;&amp; (satcab)</td>
</tr>
<tr>
<td>terrestrial</td>
<td>rand () &lt; 0.708</td>
</tr>
<tr>
<td>terrestrial2</td>
<td>(colourTV2) &amp;&amp; (terrestrial)</td>
</tr>
<tr>
<td>video2</td>
<td>(colourTV2) &amp;&amp; (video)</td>
</tr>
</tbody>
</table>

11.5.3.5 ICT
The TUS survey provides us with a flag as to whether a home has a personal computer or not. Table 53 shows additional information which is derived from existing TUS data. Because of the scarcity of real data for multiple ownerships of ICT products these data are largely estimates.
### Table 53 ICT appliance ownership

<table>
<thead>
<tr>
<th>ICT</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>charger1</td>
<td>YES</td>
</tr>
<tr>
<td>charger2</td>
<td>(adults + Children8to15) &gt; 1</td>
</tr>
<tr>
<td>charger3</td>
<td>(adults + Children8to15) &gt; 2</td>
</tr>
<tr>
<td>charger4</td>
<td>(adults + Children8to15) &gt; 3</td>
</tr>
<tr>
<td>charger5</td>
<td>(adults + Children8to15) &gt; 4</td>
</tr>
<tr>
<td>charger6</td>
<td>(adults + Children8to15) &gt; 5</td>
</tr>
<tr>
<td>fax</td>
<td>rand () &lt; 0.11</td>
</tr>
<tr>
<td>ICT</td>
<td>6</td>
</tr>
<tr>
<td>monitor</td>
<td>pc</td>
</tr>
<tr>
<td>monitor2</td>
<td>pc2</td>
</tr>
<tr>
<td>monitor3</td>
<td>pc3</td>
</tr>
<tr>
<td>monitor4</td>
<td>pc4</td>
</tr>
<tr>
<td>pc2</td>
<td>(pc) &amp;&amp; ((adults + Children8to15) &gt; 1) &amp;&amp; (rand() &lt; 0.75)</td>
</tr>
<tr>
<td>pc3</td>
<td>(pc2) &amp;&amp; ((adults + Children8to15) &gt; 2) &amp;&amp; (rand() &lt; 0.75)</td>
</tr>
<tr>
<td>pc4</td>
<td>(pc3) &amp;&amp; ((adults + Children8to15) &gt; 3) &amp;&amp; (rand() &lt; 0.75)</td>
</tr>
<tr>
<td>phone</td>
<td>YES</td>
</tr>
<tr>
<td>printer</td>
<td>(pc)</td>
</tr>
<tr>
<td>printer2</td>
<td>(pc2)</td>
</tr>
<tr>
<td>printer3</td>
<td>(pc3)</td>
</tr>
<tr>
<td>printer4</td>
<td>(pc4)</td>
</tr>
</tbody>
</table>

### 11.5.3.6 Miscellaneous

discussion of the miscellaneous items defined in the model. While it is likely that many other products would fit into this category, for example kitchen gadgets, data is scarce. However many of these appliances are likely to be low power and used for short periods of time. Again these data are based on the findings in Chapter 3.

Bathroom habits are defined to allow us to specify a period spent in the shower and drying hair, since these activities are sequential, variable in duration and require significant power.

### Table 54 Miscellaneous appliance ownership and bathroom habits.

<table>
<thead>
<tr>
<th>Miscellaneous</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>bathroom_habit</td>
<td>YES</td>
</tr>
<tr>
<td>boiler</td>
<td>YES</td>
</tr>
<tr>
<td>boilerSB</td>
<td>YES</td>
</tr>
<tr>
<td>dummy</td>
<td>YES</td>
</tr>
<tr>
<td>hairdryer</td>
<td>rand () &lt; 0.94</td>
</tr>
<tr>
<td>hairstraighteners</td>
<td>rand () &lt; 0.47</td>
</tr>
<tr>
<td>heater</td>
<td>rand () &lt; 0.8</td>
</tr>
<tr>
<td>iron</td>
<td>YES</td>
</tr>
<tr>
<td>shower</td>
<td>rand () &lt; 0.35</td>
</tr>
</tbody>
</table>
11.5.3.7 Wet
The ownership data for washing machines tumble dryers and washing machines are all provided by the TUS data. Habits are not defined because the narrative interpretations use a simple one to one mapping described later. Combination washer dryers are not modelled.
11.5.4 Appliance definitions

Appliances exhibit a range of electrical characteristics, some steady state, some executing a fixed programme, some responding to environmental conditions. The modelling framework does not in itself describe any appliance behaviour, instead a simple XML dialect is used to define all machines. Whilst this may seem overly elaborate, it does allow for incremental model development. For example, as per earlier approaches, an appliance can be modelled as a fixed level of power for a given period allowing for a rapid approximation of power flow. We might, however, have a power flow trend captured by a power analyser, for example the washing machine profiles shown in chapter X. In this case a more realistic power flow can be modelled by using the sampled data instead of a simple fixed load. Theses two basic approaches require a model definition that comprises just two or three settings and two or three parts, defined in a few lines of XML text. In this way a model can be quickly developed using simple load definitions and augmented with field data as it becomes available.

If we wish to approximate the behaviour of the home energy systems more closely then additional aspects of the domestic energy system can also be modelled. For example, again using the example of the washing machine, heating of hot water will take longer under low voltage conditions and visa versa. We could model this by ‘replaying’ the trend at different rates depending on the local voltage, in other words stretching the trend at low voltage and visa versa. However this approach would also distort the profile of the motor activity, which is not dependent on temperature. Given these caveats, to create a realist model of a washing machine that responds to environmental conditions it is necessary to simulate sub components or ‘parts’ individually. Similarly cold appliances present some complexity in that they respond to and affect their thermal environment. Given the breadth of options for modelling the various appliance types, a number of approaches have been adopted to suit the availability of data and model complexity.

112 Many appliances can be defined by on, off, and perhaps a standby
113 The size of memory used by a model can also be prohibitive for example if many large sampled trends are used.
If one approach is used per appliance type then this allows the creation of an appliance template which can be modified to represent specific variants. The following section now describes the approach used for modelling these complex appliance types.

11.5.4.1 Refrigerators and Freezers
For the refrigerator, freezer and fridge-freezer model templates, a ‘lumped’ heat flow model is used based largely on a paper by Hessami (Hessami 1991). In using such an approach, modelling of real-time thermodynamic effects is abandoned in favour of using pre-calculated thermal conductance coefficients.

The efficiency of refrigeration equipment is determined by the ambient and target temperatures, the insulation and the efficiency of the heat pump system known as the Coefficient Of Performance (COP). COP is the ratio of energy transferred to the energy used, and can vary for different designs and operating conditions. Sattar et al, conducted experiments with different refrigerants over different operating conditions and identifying ranges of COPs (Sattar, Saidur et al. 2007). COPs reported where typically in the range of 1.5 – 3, but dependant on condenser and evaporator temperatures. Consistent with the physics of heat pump or Carnot efficiency, the colder the evaporator and the warmer the evaporator the lower the COP.

The remaining parameters for the definition of the cold appliances were gathered using two methods: reviewing web based sales literature and visiting show rooms to measure appliance insulation thicknesses. These data expose some common characteristics in appliance sizing, and insulation thickness, which in helps to simplify the template design.
Figure 57 is a graphical representation of the XML template used to define refrigerators and freezers. In essence it comprises three thermal masses, the evaporator, shelves and some food contained within an insulated mass of air. The block arrows represent the direction of heat flow.

On each model *tick* heat transfer occurs between all the thermal masses, depending on their temperature differences and thermal conductivity. This function is passive in that it occurs every cycle with no active parts being required. The only active parts in this template are the heat exchanger, thermostat and sample player used to mimic the compressor motor. If the temperature is above the target temperature plus a hysteresis value, then model enters the on state; the motor load profile is replayed and joules are transferred from the evaporator to room. The off state is resumed when the temperature is below the target temperature minus the hysteresis value.

Trial simulations showed that the thermal masses within the model have a significant effect on the cycling period of the compressor. With no internal thermal mass the temperature oscillates rapidly due to the extremely low thermal mass of air.
Figure 58 shows an excerpt from a refrigerator definition that describes the thermal masses model. This example is now deconstructed to explain the various thermal model parameters.

```
<container>
  <name>appliance casing</name>
  <capacity>936.54</capacity>
  <volume>936.54</volume>
  <temperature>airTemp</temperature>
  <VHC>3.54</VHC>
  <U>100.0</U>
  <container>
    <name>fridge cabinet</name>
    <volume>75000.0</volume>
    <temperature>fridgeTemp</temperature>
    <VHC>0.001297</VHC>
    <U>10.0</U>
    <container>
      <name>Glass shelves</name>
      <volume>817.67</volume>
      <temperature>fridgeTemp</temperature>
      <VHC>2.10</VHC>
      <U>10.0</U>
    </container>
    <container>
      <name>Chilled food</name>
      <volume>5000.0</volume>
      <temperature>fridgeTemp</temperature>
      <VHC>3.50</VHC>
      <U>100.0</U>
    </container>
    <container>
      <name>evaporator</name>
      <volume>1000.0</volume>
      <temperature>fridgeTemp</temperature>
      <VHC>4.18</VHC>
      <U>10.0</U>
    </container>
  </container>
</container>
```

**Figure 58 Thermal model excerpt from a refrigerator definition.**

**<name>fridge_cabinet</name>**

This parameter is used by machine parts to identify what thermal mass they are affecting or sensing. For example a thermostat part requires a temperature source to monitor.

**<volume>75000.0</volume>**

Defines the volume of material/fluid in the container at start up time (in cm³). Volume can change in a model within the bounds of zero to the capacity parameter. In this case because no capacity is specified it is assumed to equal volume.
<temperature>fridgeTemp</temperature>
Defines the initial temperature of the material in the container. If the field does not contain a number, then a matching parameter must exist in the home parameters file, allowing variable start conditions.

<VHC>0.001297</VHC>
Defines the volumetric heat capacity of the material (in j/K/cm$^3$).

<U>0.82</U>
Defines the total heat transfer for the container (in W/K).
Note that high dummy values are used for the transfer between internal parts, since data was not available and would have been complex to calculate.

Twenty different fridges and twenty different freezers are implemented using the above template values calculated using a spreadsheet. Two spreadsheets where developed to calculate the parameters in order to mimic the variance in old and new designs. In this way a hypothetical 1995 fleet and 2010 fleet of each type was defined.

<table>
<thead>
<tr>
<th>Spreadsheet filename</th>
<th>Appliance filenames (.xml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fridge_Volumes_hist_1995.xls</td>
<td>Fridge_1995_01 to Fridge_1995_10</td>
</tr>
<tr>
<td>Fridge_Volumes_hist_2010.xls</td>
<td>Fridge_2010_01 to Fridge_2010_10</td>
</tr>
<tr>
<td>Freezer_Volumes_hist_2010.csv</td>
<td>Freezer_2010_01 to Freezer_2010_10</td>
</tr>
</tbody>
</table>

11.5.4.2 Fridge-freezers
The fridge-freezer template is an extension of a freezer template. A refrigerator cabinet is added and cooled by air flow from the freezer cabinet. This mimics a common design approach used outside the UK, and avoids the complexity of modelling designs that use two evaporators and one compressor. However the net energy use of these designs should be similar for reasons already discussed.
Table 56 Filenames of fridgefreezer model definitions.

<table>
<thead>
<tr>
<th>Spreadsheet filename</th>
<th>Appliance filenames (.xml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FridgeFreezer_Volumes_hist_1995.xls</td>
<td>FridgeFreezer_1995_01 to FridgeFreezer_1995_06</td>
</tr>
<tr>
<td>FridgeFreezer_Volumes_hist_2010.xls</td>
<td>FridgeFreezer_2010_01 to FridgeFreezer_2010_06</td>
</tr>
</tbody>
</table>

Figure 59 Fridge-freezer schematic.
11.5.4.3 Ovens
The oven template is a modified fridge template with its function reversed. The heat exchanger is replaced by a heater element, switched on when the temperature falls below target. No attempt was made to define old and newer ovens. 16 variants were defined to account for the various oven sizes.

![Figure 60 Oven schematic.](image)

Table 57 Filenames of oven model definitions.

<table>
<thead>
<tr>
<th>Spreadsheet filename</th>
<th>Appliance filenames (.xml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oven_Volumes_hist_1995.xls</td>
<td>Oven_01 to Oven_16</td>
</tr>
</tbody>
</table>

11.5.4.4 Washing machines and Dishwashers
The most complex machine type to model is perhaps the washing machine. It cannot be captured by a universal template since as identified earlier, wash programme processes vary. However this is somewhat mitigated by machines using similar logic for different settings. In line with the findings in the previous chapter, three heating control strategies were modelled, specifically:

- Heat water to target and stop heating for rest of wash.
Beyond the heating strategy, the machines all have 4 rinses and spins and a final power full spin. The spin pattern, and agitation load patterns are recalled from samples, and the water heating described by a physical model, seen in figure 6.1

Within these control strategies we can model a range of machines by adjusting water capacity, heater element wattage, drum insulation, with a range of programmes by changing target temperatures, water volumes, agitation duration and agitation profile.

The washing machines implemented are close copies, or variants, of machines sampled and described in the previous chapter. Each machine has duplicate settings namely short and cotton settings at 30, 40, 60 and 95 degrees centigrade. All machines were augmented to be capable of pausing until off peak based on an external signal.

Dishwashers conform to the washing machine schematic in that they fill with water, heat water, and empty water and ‘replay’ sampled data to simulate motor activity. To
create some diversity in the model, ten washing machines and ten dishwashers were defined. The model fleets were adapted to make their energy consumption conform to typical appliances for their respective years. This adaption took three forms. Firstly the more energy intensive heating strategies were applied to the older machines and vice versa. Secondly the water volume was increase in the older models. Thirdly, for dishwashers target temperatures were modified, typically 65 centigrade for older models and 55 centigrade for new. Assumptions for these changes were based on data collected in chapter 11 and the references indentified in table 58 below.

<table>
<thead>
<tr>
<th>References</th>
<th>Appliance filenames (.xml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(MTP 2008)</td>
<td></td>
</tr>
<tr>
<td>(Stamminger 2006)</td>
<td>WashingMachine_2010_01 to WashingMachine_2010_05</td>
</tr>
<tr>
<td>(Ennen 2006)</td>
<td>DishWasher_1995_01 to DishWasher_1995_05</td>
</tr>
<tr>
<td>(MTP 2006)</td>
<td>DishWasher_2010_01 to DishWasher_2010_05</td>
</tr>
</tbody>
</table>

### 11.5.4.5 Other appliances

Most of the remaining appliances, for example consumer and ICT products are simply a set of settings which reflect a single complex impedance or constant power characteristics. All of these are built automatically by a small helper application using the data found in autoAppliances.csv which can be found in the appendix. The exceptions to the above are the electric hobs which provide pulsed power. These are also built by a small helper application which uses the data found in autoHobs.csv in the appendix. All the data used by the helper function to build the appliances, is as sampled by the author and presented in the previous chapter or as referenced in chapter 3.

There is one final exception to the above and that is the domestic heating system which is assumed to be a gas combination boiler in all cases. Hot water supply from the boiler is not currently modelled. Files ‘combi.xml’ and ‘thermostat.xml’ in the appendix can be viewed by the interested reader.
11.5.5 Appliance distribution

Since there are many different models of each appliance type it is necessary to allocate each home a given set of appliances, as described earlier. This is handled automatically for lighting but other appliance allocation must be made explicit. In the network structure definition, each home has a different file that is requires to populate its home. In most cases the distribution of appliances is purely random, for example televisions are selected randomly from the examples surveyed by in chapter 10. However, with some appliances for example freezer and ovens, it is desirable to use a spread of typical sizes and ratings.

To this end, the macro.csv files found in the home information folders of the appendix show the various appliance distributions. Their spreadsheet source data can also be found in the appendix.

11.5.6 Weather data

For the purposes of the scenarios modelled, only sunlight and ambient temperature data is required; no effects of wind on building temperature and no wind micro-generation is modelled. Because of the above, it was possible to use data from a recent UK government solar panel trial (BERR 2007), comprising ambient temperature, sunlight on horizontal axis and sunlight on solar panel axis. The complete dataset comprises data from tens of sites at 5 minute resolution for the whole of 2005, providing a wide range of weather conditions. For the purposes of this model these large data were cropped into a number of daily profiles. More specifically, dates were selected that match the sunrise and sunset times when the profile class data was collected, namely the 10th of November and the 14th of January (Spencer 2010).
11.5.7 Narrative rules and habit definition assumptions

The narrative rules data provide the means to translate abstract diary data into specific activations of appliances. The modelling framework provides two approaches to modelling behaviour.

The primary mechanism is the narrative interpreter which activates appliances based on arbitrary expressions. For example table 59 demonstrates how we can provide a spread of settings for washing machine usage.

<table>
<thead>
<tr>
<th>Start</th>
<th>Stop</th>
<th>Activity</th>
<th>Rule</th>
<th>Action</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>04:00:00</td>
<td>03:59:59</td>
<td>Laundry</td>
<td>( \text{rnd} \leq 0.68 )</td>
<td>washingmachine</td>
<td>cotton 40</td>
</tr>
<tr>
<td>04:00:00</td>
<td>03:59:59</td>
<td>Laundry</td>
<td>( \text{rnd} &gt; 0.68 ) &amp;&amp; ( \text{rnd} &lt; 0.98 )</td>
<td>washingmachine</td>
<td>cotton 60</td>
</tr>
<tr>
<td>04:00:00</td>
<td>03:59:59</td>
<td>Laundry</td>
<td>( \text{rnd} &gt; 0.98 ) &amp;&amp; ( \text{rnd} \leq 1.0 )</td>
<td>washingmachine</td>
<td>cotton 95</td>
</tr>
</tbody>
</table>

In this example occupants are considered to have started a wash whenever they stated that they were performing laundry. These rules are the same throughout the day, as indicated by the start and stop periods. Since the value of ‘\( \text{rnd} \)’ is persistent between rules a spread of use is created where 68% of washes are 40 degree cotton.

It is important to remember that such rules may produce overly high appliance usage, since other laundry activities such as sorting clothes may be recorded in a diary as ‘laundry’. This can be mitigated by lowering the probability of each setting respectively but maintaining the same distribution\(^{114}\).

The second approach, as described earlier, is to encapsulate more complex behaviour in ‘habits’ using the same XML dialect used to describe machines. It is possible to produce an individual narrative for each household, or alternatively a universal narrative that contains enough variety to mimic all households. The latter approach was taken for the purposes of this thesis in order to minimise the complexity in calibrating the model. With all the narrative rules in one file, it is relatively straightforward to adjust and test the population’s behaviour.

\(^{114}\) This kind of fitting is possible because the framework logs and ex-post reports on all appliance usage.

270
A number of variable interpretations where added to the output of the TUS to provide additional Boolean variables for the narrative engine. For example ‘male’ and ‘female’ allow us to activate different habits for the different sexes. The following subsections now identify the key approaches used to mimic occupant behaviour in respect of the various appliance categories. Also, to simplify the narrative rule set, the TUS translations tables was amended: similar activities were renamed, for example ‘watching sport on TV’ and ‘watching a film on TV’ both became ‘watching TV’. Computer usage was treated in a similar manner.

11.5.7.1 Lighting
All lighting is activated using a simple rule of ‘(light < x)’, or ‘(mood_lounge && light < x)’, the light variable being the outside ambient light level. This allows the activation of lighting at levels appropriate for different rooms and activities, for example it is usual to have a bright kitchen for cooking. In addition, some lights are switched on, irrespective of activity, if they are part of the ‘mood lighting’ variables as described earlier.

Selecting a light level at which a bulb should be switched on is not straightforward. To minimise complexity, in this instance no attempt is made to model individual rooms and their window aspects thus ‘x’ must include the reduction of light caused by windows. Secondly it is clearly a matter of preference as to what light level is comfortable for a given individual for a given activity. Thirdly, lighting levels vary according to room colour and furnishings.

These issues are however mitigated by a number of factors, firstly a light bulb being switched on relates primarily to whether a room is in use. The lighting profiles used demonstrates that in winter dusk falls rather rapidly, thus the trigger level will often only be significant during a short period before night fall.

Given the above, the approach used is to define a range of levels for different activities, consistent with those used in previous models (Richardson, Thompson et al. 2007). Trigger levels were selected on the principle that some activities require more
light than other. For example preparing food requires an ambient light level higher than watching television. The trigger values are also varied stochastically.

Table 60 Example activity based lighting.

<table>
<thead>
<tr>
<th>Time</th>
<th>Action</th>
<th>Conditions</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>04:00:00</td>
<td>Laundry</td>
<td>light &lt; (1.0 + rand()) * 25.0</td>
<td>light_kitchen_1</td>
</tr>
<tr>
<td>04:00:00</td>
<td>Laundry</td>
<td>light &lt; (1.0 + rand()) * 25.0</td>
<td>light_kitchendiner_1</td>
</tr>
</tbody>
</table>

Table 61 Example mood based lighting.

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Conditions</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>04:00:00</td>
<td>Laundry</td>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (mood_kitchendiner_1)</td>
<td>light_kitchendiner_1</td>
</tr>
<tr>
<td>04:00:00</td>
<td>Laundry</td>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (mood_kitchendiner_2)</td>
<td>light_kitchendiner_2</td>
</tr>
<tr>
<td>04:00:00</td>
<td>Laundry</td>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (mood_kitchendiner_3)</td>
<td>light_kitchendiner_3</td>
</tr>
<tr>
<td>04:00:00</td>
<td>Laundry</td>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (mood_kitchendiner_4)</td>
<td>light_kitchendiner_4</td>
</tr>
<tr>
<td>12:00:00</td>
<td>Laundry</td>
<td>light &lt; (1.0 + rand()) * 25.0 &amp;&amp; (mood_lounge_1)</td>
<td>light_lounge_1</td>
</tr>
<tr>
<td>12:00:00</td>
<td>Laundry</td>
<td>light &lt; (1.0 + rand()) * 25.0 &amp;&amp; (mood_lounge_2)</td>
<td>light_lounge_2</td>
</tr>
<tr>
<td>12:00:00</td>
<td>Laundry</td>
<td>light &lt; (1.0 + rand()) * 25.0 &amp;&amp; (mood_lounge_3)</td>
<td>light_lounge_3</td>
</tr>
<tr>
<td>12:00:00</td>
<td>Laundry</td>
<td>light &lt; (1.0 + rand()) * 25.0 &amp;&amp; (mood_lounge_4)</td>
<td>light_lounge_4</td>
</tr>
</tbody>
</table>

11.5.7.2 Cooking

While cooking appliances are relatively straightforward to model, mimicking how they are used presents a challenge. Data on meals and cooking methods is scarce and there is a wide variation in energy used for the preparation of the same meal (Mansouri, Newborough et al. 1996).

The Mansouri et al. hob usage data presented in chapter 2 is revealing. Firstly it informs us that the majority of cooking is performed on the higher power hob rings, 1 and 2; the smaller rings, 3 and 4 are not used in around 50% of cooking events; and shorter cooking activities are more likely to use the smaller hobs.

Whilst it does not give us an indication of diurnal distribution, these data do give us a starting point to create narrative rules, define habits and a means to test their effect. A spread of ‘hob use habits’ are defined reflecting the above, and these are triggered stochastically in the narrative during ‘food preparation’ events, an excerpt of which is shown in table 62.

Table 62 Example excerpt of meal habit action rules (note time and activity name have been removed to allow them to fit on the page.)

<table>
<thead>
<tr>
<th>Recipe</th>
<th>Time</th>
<th>Conditions</th>
<th>Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>kitchen_habit_cookfor2</td>
<td>(rnd &lt;= 0.1) &amp;&amp; (occupants == 2)</td>
<td>pizza</td>
<td></td>
</tr>
<tr>
<td>kitchen_habit_cookfor2</td>
<td>(rnd &gt; 0.1) &amp;&amp; (rnd &lt;= 0.2) &amp;&amp; (occupants == 2)</td>
<td>frozenreadymeal</td>
<td></td>
</tr>
<tr>
<td>kitchen_habit_cookfor2</td>
<td>(rnd &gt; 0.2) &amp;&amp; (rnd &lt;= 0.3) &amp;&amp; (occupants == 2)</td>
<td>indiansreadymeal</td>
<td></td>
</tr>
<tr>
<td>kitchen_habit_cookfor2</td>
<td>(rnd &gt; 0.3) &amp;&amp; (rnd &lt;= 0.4) &amp;&amp; (occupants == 2)</td>
<td>fishfingersandchips</td>
<td></td>
</tr>
</tbody>
</table>
(rnd > 0.4) && (rnd <= 0.5) && (occupants == 2) kitchen_habit_cookfor2 lasagne
(rnd > 0.5) && (rnd <= 0.6) && (occupants == 2) kitchen_habit_cookfor2 roastchickenMEAL
(rnd > 0.6) && (rnd <= 0.7) && (occupants == 2) kitchen_habit_cookfor2 salmonfilletMEAL
(rnd > 0.7) && (rnd <= 0.8) && (occupants == 2) kitchen_habit_cookfor2 curryMEAL
(rnd > 0.8) && (rnd <= 0.9) && (occupants == 2) kitchen_habit_cookfor2 pastaMEAL
(rnd > 0.9) && (rnd <= 1.0) && (occupants == 2) kitchen_habit_cookfor2 stirfryMEAL

11.5.7.3 Cold
The only narrative rules that apply to cold appliances relate to the opening of the appliance doors. A special function was added to the machine object that exchanges cold air from the appliance with air from the room.

11.5.7.4 Wet
The rules for wet appliances are as described earlier in introduction of this section.

11.5.7.5 ICT and Consumer
Activities in these categories are treated in a straightforward manner, with related appliance being switched on for the period of the activity. For example when a computing activity is occurring, then a computer and a monitor, if necessary are switched on. One complexity however is that homes can own several computers. Table 63 demonstrates how different occupants can use different computers depending on their availability. A similar approach is used for all electronic goods of which there may be several available. Also note how some effort is made to associate different appliances with different rooms. See the appendix for the full narrative rule set.

Table 63 Rules to ensure multiple PCs are used when available.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (PersonNo == 1)</td>
<td></td>
</tr>
<tr>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (PersonNo == 1)</td>
<td></td>
</tr>
<tr>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (PersonNo == 1)</td>
<td></td>
</tr>
<tr>
<td>(pc2)</td>
<td>pc on</td>
</tr>
<tr>
<td>(pc2)</td>
<td>monitor on</td>
</tr>
<tr>
<td>(pc2)</td>
<td>modem on</td>
</tr>
<tr>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (pc2) &amp; (PersonNo == 2) &amp;&amp; (pc3))</td>
<td>light_bedroom1_1 on</td>
</tr>
<tr>
<td>(pc2) &amp; (pc3)</td>
<td>pc2 on</td>
</tr>
<tr>
<td>(pc2) &amp; (pc3)</td>
<td>monitor2 on</td>
</tr>
<tr>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (pc3) &amp; (PersonNo == 3) &amp;&amp; (pc4))</td>
<td>light_bedroom2_1 on</td>
</tr>
<tr>
<td>(pc3) &amp; (pc4)</td>
<td>pc3 on</td>
</tr>
<tr>
<td>(pc4)</td>
<td>monitor3 on</td>
</tr>
<tr>
<td>(light &lt; (1.0 + rand()) * 25.0) &amp;&amp; (pc4) &amp; (PersonNo == 4) &amp;&amp; (pc5))</td>
<td>light_bedroom3_1 on</td>
</tr>
<tr>
<td>(pc4) &amp; (pc5)</td>
<td>pc4 on</td>
</tr>
<tr>
<td>(pc4) &amp; (pc5)</td>
<td>monitor4 on</td>
</tr>
</tbody>
</table>
11.5.8 Network structure

Whilst a great deal of textbook literature discusses issues and strategies for network planning (for example (Willis 1997) ) details of specific UK networks are scarce. In order to understand the specific details of UK distribution networks a number of informal discussions were held with power system experts\(^{115}\) and then details confirmed with a network operator\(^{116}\) and DNO operation manuals (Salmon 2006).

From these discussions it transpired that a number of assumptions can be made about a typical domestic feeder network, namely:

- There are typically around 160 domestic properties connected to a single substation.
- A single substation normally has up to and typically 4 feeder cables.
- Cables tend to run on both sides of a street, under the pavement.
- Adjacent neighbours should be wired to different phases\(^{117}\) but are often not because of the physical lay of the cable. The top phase is more accessible so tends to be over-used, especially with larger cable diameters (Smiles 2008).

There are however cultural differences between DNOs, and between old and newer installations:

- In London, currently (currently managed by EdF), feeder cables are of a uniform thickness from start to end. This is because the network was previously ‘meshed’ at LV for resilience, allowing equal current to flow in either direction (Salmon 2006; Smiles 2008).
- Whilst the network configuration in London is now radial, i.e. substation circuits are not interconnected at LV, the fitting of uniform cable thickness persists.
- In the north of England cable thickness was tapered, consistent with a culture of radial configuration of networks (Smiles 2008).
- Cables have 4 cores, three live phases and a neutral return.

---

\(^{115}\) Prof. Tim Green, Prof. Goran Strbac, Cliff Walton and Tony Woods of Imperial College.

\(^{116}\) Paul Smiles of EdF.

\(^{117}\) Typically red-yellow–blue–red–yellow–blue, or r-y-b-b-y-r.
- In London existing (pre 1985) three phase cable is either copper or aluminium, with lead sheath and steel armour and conductors are typically 240mm$^2$, rated 400 Amp per phase.
- New cable laid in London is 300mm$^2$ aluminium.
- The neutral core is usually one cable grade thinner than lives.
- Outside London tapering means feeder cable can range from 300mm$^2$ down to 32mm$^2$.
- Houses can be three phase (larger properties) but are typically single phase.
- Spurs to houses are typically 32mm$^2$ copper.

Bringing these issues together, it appears that it is possible to develop a realistic topology that will reflect real networks. For example the simplest structure would be two streets of 80 houses, two feeders per street. Allowing for a span of cable from the substation to the start of the street, for given cable types, we can define appropriate impedances for this network from just three variables: length of cable to street, property plot width, property distance from pavement.

Here the key variables in a residential LV feeder are the distance between houses at the street, and the length of the spur to the property. More complicated arrangements see ‘back to back’ properties and flat conversions where one spur feeds two or more properties with ‘sub spurs’ to each part of the building\textsuperscript{118}.

The actual impedance of these cable types is available in sales literature from cable companies; the table below collates 3 phase copper and aluminium cable impedance data from BATT cables.

\textsuperscript{118} The authors Victorian conversion flat being an example.
Table 64 Typical impedances of underground feeder cables (BATT 2008; BATT 2008)

<table>
<thead>
<tr>
<th>Cable diameter (mm²)</th>
<th>Copper</th>
<th>aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rating (A)</td>
<td>R (mΩ/m)</td>
</tr>
<tr>
<td>25</td>
<td>96</td>
<td>1.60</td>
</tr>
<tr>
<td>35</td>
<td>115</td>
<td>1.35</td>
</tr>
<tr>
<td>50</td>
<td>135</td>
<td>0.99</td>
</tr>
<tr>
<td>70</td>
<td>167</td>
<td>0.67</td>
</tr>
<tr>
<td>95</td>
<td>197</td>
<td>0.50</td>
</tr>
<tr>
<td>120</td>
<td>223</td>
<td>0.40</td>
</tr>
<tr>
<td>150</td>
<td>251</td>
<td>0.32</td>
</tr>
<tr>
<td>185</td>
<td>281</td>
<td>0.25</td>
</tr>
<tr>
<td>240</td>
<td>324</td>
<td>0.20</td>
</tr>
<tr>
<td>300</td>
<td>365</td>
<td>0.16</td>
</tr>
</tbody>
</table>

As this table demonstrates the use of aluminium cable necessitates an increased conductor area to obtain similar specification, although moving up one cable class still results in a lower capacity and higher impedance. Applying these data to typical cable lengths, results in network impedances shown in table 65.

Table 65 Impedances (mΩ) for fixed lengths of feeder and spurs cables in LV network.

<table>
<thead>
<tr>
<th>Meters (m)</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable type</td>
<td>R</td>
<td>x</td>
<td>r</td>
<td>X</td>
<td>r</td>
</tr>
<tr>
<td>35mm Copper</td>
<td>1.35</td>
<td>0.155</td>
<td>6.75</td>
<td>0.775</td>
<td>13.5</td>
</tr>
<tr>
<td>240mm Copper</td>
<td>0.2</td>
<td>0.14</td>
<td>1</td>
<td>0.7</td>
<td>2</td>
</tr>
<tr>
<td>240mm Aluminium</td>
<td>0.28</td>
<td>0.125</td>
<td>1.4</td>
<td>0.625</td>
<td>2.8</td>
</tr>
<tr>
<td>300mm Aluminium</td>
<td>0.23</td>
<td>0.125</td>
<td>1.15</td>
<td>0.625</td>
<td>2.3</td>
</tr>
</tbody>
</table>

For the purposes of the scenarios to follow a network description was defined that assumes a 20m feeder from the substation to each side of two streets. Each house is then assumed to be 5m apart, with the electricity meter 10m from the street. This might represent a Victorian terrace as seen in London, but without any houses being divided into flats. The 35mm cable values above are used as a proxy for 32mm values.
11.5.9 Case study 1

‘What does power flow on a residential feeder on a look like in terms of active power, reactive power and losses?’

This first illustration focuses on modelling the demand profile for a domestic winter weekday, using the assumptions described in the previous sections. A model neighbourhood is defined in XML which represents 1600 homes, comprising 40 homes on four feeders. In this and later case studies, the network is populated and run 10 times, resulting in a total pollution of 1600 homes. In each iteration the TUS households selected, narrative behaviour and appliance ownership statistic are calculated using a preselected random seed; this both ensures that each execution of the model is distinct but also repeatable.

No load shape fitting is attempted except for a distribution of small dummy loads to raise the base load level to 0.2 kW, as seen in the measured profile. These dummy loads are in this instance recorded as miscellaneous load, however in practice they may be due to lighting, ICT or consumer goods that are left on or items such as fish tank equipment or electric heaters. The intention of not attempting to iteratively fit the demand curve by modifying the narrative rules was to ascertain to what extent a simple narrative rule mapping would produce realistic results, and more importantly not to start fitting the profiles with potentially spurious rules in the absence of survey data.

Figure 62 presents a 5 second resolution\(^\text{119}\) 24 hour profile for one 160 household neighbourhood. Here we can see the dramatic difference between a local and the nation profile.

\(^\text{119}\) This is the maximum resolution that can be handled in an Excel spread sheet.
Figure 62 High resolution demand profile for 160 homes over 24 hours.

With each phase represented separately there are clearly wide temporal variations within each phase and between phases. It is of interest that the variance of demand is of a similar magnitude to the moving average. Reactive power fluctuates between leading in the early morning and evenings to lagging during the day. This suggests that electronic loads, that are typically current leading, more than compensate for the current lagging load of cold appliances during the evening.

As expected the temporal variations of losses are even more marked than those of the active power flow. Figure 63 shows the live and neutral losses for the demand profile shown in figure 62. The losses on the neutral have been inverted and the x axis labels removed for clarity.
This figure demonstrates how the current flow on the neural, and hence neutral losses, relate to the imbalance between the live phases. The network model in question is of relatively low impedance, and well balanced so the absolute losses are low, but this profile demonstrates the dynamic nature of losses, the additional value of avoiding peak demand and in keeping a low voltage networks balanced.

Figure 64 shows the half hourly average demand curve for a 10 model iterations, or 1600 homes. As can be seen from the trend produced, the demand curve matches the measured data fairly closely. The model and profile class 01 curves in this scenario have a correlation coefficient of over 0.98. The main points of interest in terms of changing model parameters would be to better match the morning and evening peaks. This profile suggests that a very accurate averaged profile could be achieved with improved narrative rules based on survey data, or perhaps better appliance ownership statistics.
The model discrepancies may be simply due to lighting habits, in which case could be easily corrected. However if we observe figure 65, we can see that there is a great deal of variance around the average which might warrant more iterations or a larger network population to be established.
In order to check the balance of energy use amongst appliance categories, it is necessary to compensate for seasonal variation in appliance usage. Rather than run the model 365 times for 1600 homes, which would have been prohibitive in terms of execution time, six scenarios were selected, namely summer Sunday, summer weekday, and summer Saturday, winter Sunday, winter weekday, and winter Saturday, with the intention of producing an estimate of demand per appliance category.

This approach is compromised however; firstly while the narrative rule set that produce a reasonably accurate curve for weekdays do not work so well for Sundays. Figure 66, show the Elexon profile class 01 ten year average profiles compared the model output for the Winter weekend.

![Figure 66 Measured average and modelled profiles for Winter Saturday and Sunday.](image)

Saturday achieves a correlation coefficient of 0.98, whereas Sunday only 0.90, and the model trend’s Sunday morning period clearly deviates from the measured data. This suggests that distinct narrative rules are required for modelling winter Sundays. With hindsight this is not surprising given the cultural differences associated with Sunday, for example the Sunday roast dinner.
Summer model profiles using the same narrative rule set also deviate somewhat from the measured data. Figure 67 shows the models output for summer weekdays, achieving a correlation coefficient of 0.91.

![Measured average and modelled profiles for Summer weekday.](image)

Considering figure 67 and 68 we can see that there are distinct excessive peaks in the morning and evening for weekdays and Saturday. This may be due to two issues, firstly since only different ten days are used for weather data, sunlight level may be below the ten year average in the model; more likely is that mood lighting is less used in Summer. The Sunday summer model trend suffers from the same issues in the evening, but with the dip in place of the peak before lunch time, as identified with winter Sunday. The modelled Summer Saturday and Summer Sunday achieve correlation coefficients of 0.93 and 0.90 respectively.

![Measured average and modelled profiles for summer weekends.](image)
While these profiles could benefit from season specific narrative rule-sets, their associated metadata are adequate for an estimation of total appliance demand. Given that the framework records the individual energy use of each appliance type, it is possible to establish the mix of appliance usage for each model execution. Figure 69 shows us the average equivalent annual energy use for each appliance category for the model and official government estimates.

![Figure 69 Base-case scenario data, total energy by appliance category.](image)

The chart totals were calculated by weighting weekday data at $\frac{5}{7}$ of the total and Saturday and Sunday weighted at $\frac{1}{7}$ of the total. The seasonal average is assumed to be $\frac{1}{2}$ the Summer average plus $\frac{1}{2}$ the Winter average.

The categories of cold, consumer and cooking agree closely with government estimates, whereas ICT, lighting and wet deviate somewhat.

The ICT category shows a wide variation in official estimates, both above the models output. It should be pointed out that computers being left on for longer than they are in use can be modelled by the framework. In this scenario a scaling factor of 6 is used to extend ‘on’ periods over and above the periods stated in the TUS. However despite this, the model still produces the lowest figures for ICT and this deserves further investigation. This discrepancy might be due to a number of factors, if the MTP
ownership data are correct, and the model stochastic are mimicking these well, then the deficiency is in the narrative rules that govern the operation of the ICT equipment. It may be that printers are turned to idle for long periods of time as opposed to being left on standby, or that some machines are left on all the time.

The model appears to over-estimate the use of lighting, and again this might be due to a number of issues. The summer profiles appear to have too much lighting in use by way of their morning and evening peaks. However, the government estimates however use relatively old bulb ownership data compared to the recent survey data used by the model, so this may be an issue.

The wet appliance category’s apparently high use may be due to narrative rules, in that perhaps sorting and folding are sometimes recorded as laundry activity, without any use of a appliance; or lower temperature washes for example 30 degrees or short washes for which there are no usage statistics are quite common.

Despite the above, the outputs from this initial model set are similar to the ranges proposed by DECC (DECC 2009) and the MTP (MTP 2008). The miscellaneous category includes electric showers, electric irons, hair dryers and vacuum cleaners, as well as the dummy loads; this category appears significant despite its absence from government data.
11.5.10 Case study 2

‘Can the automated deferral of wet appliances provide significant peak shaving?’

In this example the input data are identical to those in the previous case except that dishwasher, washing machine, and tumble dryer programme starts are paused if initiated between 4.30pm and 9.30 pm. An initial test case was developed which used a simple on/off code for all machines, but whilst this did reduce the evening peak it introduced a later but sharper and higher peak later in the evening. The framework’s ‘remoteSwitch’ appliance component allows different machines to respond to different trigger codes and this was utilised to develop a phased switching strategy. The switching pattern used in this scenario staggered the switch on times of neighbouring household appliances by 5 minutes, with the top home of each feeder switching on first, followed by the second five minutes later and so on.

This approach rectified the second peak problem and the resulting profile can be seen in figure 70, it suggests that wet appliances deferral could have significant positive effects. In this example of 1600 homes, the top of the peak at 6.30m is reduced by 4% with reductions reaching 6% at 7.30pm. The load reduction trend shows the peak-shave and associated comeback load.
Figure 70 Averaged model demand curve for 1600 homes, for base-case and wet appliance deferral.

Figure 71 Variability in model half hourly demand profiles for 160 home averages with wet appliance deferral (profile class 01 curve in blue bold).
Figure 71 show that, as with the base-case scenario there is a wide variety between profiles, and that the peak shaving effect will be different for different neighbourhoods.

We can confirm that washing machine loads have been shifted by observing the high resolution profile data with reactive power. Figure 72 shows low levels of lagging reactive power, as seen with washing machines, occurring in the evening peak period. It also suggest that the ‘pause period’ for washing machines might prove even more effective if started earlier since some washes take over an hour and a half, causing some wash spins around peak.

![High resolution 24 hour demand profile for 160 homes with wet appliance deferral.](image)

This said the large amount of reactive power in the morning and afternoon suggest that most laundry activity is not conducted at peak, thus explaining the relatively modest effect of peak shaving.
11.5.11 Case study 3

‘Does reactive power flow in residential feeders have any significant effect?’

This scenario simply involves the running of the base-case scenario with the framework set to ‘drop VARS from samples’ mode. The addition of this feature avoided the unnecessary complexity of defining a host of machines with an improved power factor. Note that this option does not remove all VAR flow from the model; rather it simply removes the VARs from motor profile samples used mainly in cold and wet appliances.

Looking at the high resolution profiles with reactive power in figure 73 we can see that, without wet and cold appliance motor activity, current flow in model is leading though-out the day.

Figure 73 High resolution demand profile for 160 homes over 24 hours.
Figure 74 shows the loss profiles associated with the same profile as figure 73. Superficially this trend looks exactly like the loss profile associated with the base-case scenario. However there are some small differences, table 66 shows the average effect of managed VARs on losses over 1600 homes.

<table>
<thead>
<tr>
<th></th>
<th>Live losses</th>
<th>Neutral losses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base-case</strong></td>
<td>6.553047</td>
<td>1.393865</td>
</tr>
<tr>
<td><strong>Managed VARs</strong></td>
<td>6.556669</td>
<td>1.399597</td>
</tr>
<tr>
<td><strong>Difference</strong></td>
<td>-0.003622</td>
<td>-0.005732</td>
</tr>
</tbody>
</table>

Interestingly managing lagging reactive power does not appear to benefit losses on either the live or neutral. Figure 75 and 76 show the temporal variation in losses for live and neutral power flows respectively.

What these figures demonstrate is that at any given time VARs can either reduce or increase losses on both the live and neutral. This is likely due to the simultaneous mix leading and lagging power flows resulting in more or less power apparent flow.
While these variations are very modest it does question whether VAR management has any merit on domestic feeders. This scenario may be worth repeating on a highly stressed system, since such difference may become more marked.
11.5.12 Summary

The three case studies presented have demonstrated some of the capabilities of the modelling framework. While low resolution outputs allow us to compare the model population behaviour against known national profiles, high resolution data allow us to investigate the detail of network behaviour. Because all stochastic aspects of the model are derived from a single seed, all scenarios can be readily reproduced verbatim or with a single aspect modified.

The base-case scenario revealed the dynamic nature of energy flows on a domestic feeder, which vary considerably from the measured half-hourly profile. The loss profile produced by a single neighbourhood is again more dynamic, and depends on the coincidence of other loads on the system. The main finding is that individual streets or neighbourhoods might vary considerably in terms of their load profile. Given that the case studies use a random mix of population demographics, analysis of different social groups, coupled with appropriate difference in appliance ownership and network structure could provide further insights. The network chosen was the equivalent to a terrace of narrow houses, and the resultant losses were comparatively low being under 0.5%.

Two interventions were tested, an automated peak-shaving technology and the passive management of reactive power.

The peak-shaving case study clearly demonstrated the potential of deferral of wet appliances. Although the peak shaving effect was modest, at around 4-6%, this is an accurate representation of what is possible. This said, as per earlier discussion other approaches might also be applicable to improving the effect of clothes and dish washing, for example the use of hot water feed. These approaches could be modelled with some modest extension to the frameworks capability which already models fluid volumes and flows.

The managed VAR case study showed, rather surprisingly, that the management of lagging reactive power may actually increase losses. It appeared that in an environment with leading or capacitive loads, in some instances the lagging power
flow helps to correct power factor and reduce losses. However this effect was shown to be extremely dynamic.

11.5.12.1 Case study carbon emissions

If we assume that the case-studies have no effect on the diurnal supply side carbon emissions we can approximate their carbon intensity using existing carbon intensity curves. Here we use the same carbon intensity curve as presented in chapter 5. Rather than using a per home average, here we consider the neighbourhoods total carbon emissions, that is including the losses of the local network.

Figure 77 presents the hourly rate of emissions for the average 160 home neighbourhood for two scenarios. The managed VARs curve is indistinguishable from the base-case so has been excluded.

These trends are more peaked in comparison to the power demand profiles, because beside the modest additional ‘load’ of network losses, the carbon curve which the power curve is multiplied against also has a daytime peak.

![Graph showing hourly emissions for two scenarios.](image)

Figure 77 Neighbourhood emissions (160 home averages) for two case studies.

The total carbon emissions associated with 160 homes for each scenario is shown in table 67. The simple peak-shaving scenario achieves almost 1% reduction.
In practice if such technology were applied on a national level, a number of additional benefits would accrue as discussed in chapter 5. The total system peak would be lower, potentially lowering the carbon intensity of the whole supply side in the evening; distribution losses would be reduced, especially on congested and imbalanced networks (unlike the model network); transmission losses would also be reduced.

Table 67 Emissions per scenario for a 160 homes neighbourhood.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Kg Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basecase</td>
<td>1117.108</td>
</tr>
<tr>
<td>Peakshave</td>
<td>1110.013</td>
</tr>
<tr>
<td>Managed VARs</td>
<td>1117.195</td>
</tr>
</tbody>
</table>
12 Conclusion

The supply of electricity to UK homes constitutes a significant cause of CO₂ emissions. Over the previous chapters the incumbent ‘supply paradigm’ has been identified as problematic, while alternative decentralised approaches face numerous and significant barriers. The list below summarises the multi-level issues that have been identified as causing inertia to change.

<table>
<thead>
<tr>
<th>Ideological framework</th>
<th>No ‘planning’, the ‘rational consumer’, ‘pro-choice’.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy framework</td>
<td>Favouring supply side over demand side solutions.</td>
</tr>
<tr>
<td>Infra-structure design</td>
<td>Centralised system topology locking in losses and creating strong path dependencies, for example metrology and its impact on retail market design.</td>
</tr>
<tr>
<td>Social norms</td>
<td>Defining the broader parameters of appliance ownership and energy use, as per Shoves 3Cs of comfort, cleanliness and convenience.</td>
</tr>
</tbody>
</table>
Imperfect information

For example decoupling of price risk and externalities from consumer, with average socialised prices.

Psychology

Habits supporting inefficient practices in individuals, as per Jackson’s meta analysis. Rationalising of existing behaviour.

Appliance technology

Providing the ‘building blocks’ of demand. With design norms predating concern about climate change.

It was argued that within this web of influences the approaches used in modelling, measurement and management of the ‘demand side’ deserve careful attention. The methods of measurement and modelling, in both the operational activities of the electricity sector and the research community have framing effects that have to date received little attention in energy policy debate.

Policy is often said to be evidence based, with an emphasis on cost-benefit analyses, but the approaches to metrology and research technology have been shaped by the needs of the centralised system. These established methods of measurement, formulating metrics and modelling then influence the nature of evidence and the choice of interventions.

Conversely, as was demonstrated in the discourse surrounding smart metering, policy development is not all about the evidence base, rather it is influenced by history, ideology, institutional frames, individual perceptions, expediency and negotiation, and is often poorly served in empirical terms.
Chapter 9 argued that the negative perceptions of the consumer may not be ‘inherent’ human attributes, but a consequence of pathways taken in system development. In turn these perceptions influence policy by framing the beliefs about what is possible in the mind of policy makers and private sector actors.

It was proposed that the unprecedented challenge of climate change warrants both a reconsideration of the roles and responsibilities, and the methods used in the search for solutions.

12.1 Measurement

Chapter 9 argued that a change in metering arrangements is necessary to facilitate a transformation of domestic energy culture. Based on historical evidence and the more recent actions of utility companies however, it unlikely that what have become known as ‘smart meters’ will themselves challenge the ‘supply paradigm’. The definition of metering standards to facilitate interoperability is likely to be mediated by the aspirations of the utilities. Moreover the evidence base for higher resolution measurement and phase measurement capability has been weak.

In examining the nature of different appliance types, chapter 10 supported earlier findings that domestic loads often fluctuate rapidly, have significant levels of reactive power flow and harmonics. These findings strengthen the argument that the modelling of domestic power flows would benefit from higher time resolution and consideration of reactive power. Using low time resolution, loads appear more benign to the system with ‘needle peaks’ and troughs filtered out of view.

The data also provided evidence that if ‘smart meters’ had the facility to record power flow at higher resolution, including reactive power, this could provide strong cues for non intrusive analysis of loads, hence improving the scope for consumer feedback and advice.

A policy recommendation was that consumers have free access to their meter data, and which is not mediated by the supplier. With the bill payer’s permission, third parties could then better understand what demand profile comprises and make
recommendations accordingly. Actors other than the suppliers may be more efficient in the delivery of information and services, and they may hold a more trusted position. Moreover community based interventions could benefit from an understanding of the local energy landscape, for example to assist in the optimal location and sizing of micro-generation.

This issue is however problematic, in that some consumers may not wish to divulge their demand profiles resulting in sparse data sets. Energy researchers focussing on theoretical benefits of interventions could use anonymous data, but mechanisms would be required to ensure the anonymity and availability.

12.2 Modelling

The review of modelling identified two distinct but complementary categories of modelling domestic energy use, econometric and ‘bottom up’ or engineering models. Bottom up modelling does not attempt to understand the consumer, as some econometric models do, but instead focuses on synthesising realistic representations of energy use. Bottom up modelling is especially appropriate for the domestic sector given the difficulties and costs of physical pilot studies.

The modelling framework described in chapter 11, allows the investigation of a range of determinants of electricity use in the home. The framework allows a clear delineation between the choice of activities, the nature of habits and appliance behaviours and in this respect provides a link between social and technical considerations. Using generalised expressions to derive appliance ownership and narratives, with the separate encoding of ‘habits’, the approach allows us to formalise the relationship between human activity and appliance usage.

As the load shape emerges as various data are input, we can reflect on the appliance ownership, narrative and habit mappings in a heuristic manner. The experience gained in developing the model parameter sets is instructive in that it raises specific questions about the nature of electricity demand and offers a means to verify top down
assumptions. However the specific detail of appliance ownership and energy using behaviour is scarce and would benefit from further survey work.

The framework demonstrates that representative models can be developed and whilst much data is required, this is to some extent mitigated by the object orientated methodology and the commonalities in social norms, habits, appliance design. To the author’s knowledge, at the time of writing the modelling framework represents the first approach capable of synthesising one second resolution domestic demand profiles including reactive power flow and losses data.

Given the need for larger model sets to achieve clearer results and for a range of networks and demographic groups, computational power may become an issue. The scenarios as described in the previous chapter take around 20 hours to run 10 iterations on a recent AMD 64-bit architecture processor running at 3.0 GHz. The processing bottleneck is processor power, as opposed to memory, so this could be to some extent mitigated by the use of machines with a multiprocessor architecture.

12.3 Management

Chapter 9 argued that in the longer term the responsibility for climate change mitigation should become more consumer focussed. If the consumer was given more responsibility in reducing carbon emissions, this would shift the emphasis from ‘market push’ by government and utilities to a ‘market pull’ on energy saving technology and energy service innovation. It was also argued that demand side participation would benefit from improved information both from metering and new approaches to modelling.

The framework presented in chapter 11 allows the analysis on individual homes or larger communities, and while the initial findings are only indicative they do provide some insights, namely:

- Neighbourhoods of 160 household, measured on a half hourly basis can vary considerably from the regional average load profile.
• Observed at a time resolution in the order of seconds, the same communities have highly erratic demand profile compared to that of the half-hourly average.
• Loss characteristics are extremely dynamic.
• The losses associated with the simple case-study network are low suggesting a wide variation in low voltage network losses.
• The net reactive power flow in the model neighbourhood fluctuates between leading and lagging throughout the day.
• It is not clear that reactive power adds significant losses on the low voltage network. The model results indicated that they may in some circumstances reduce losses but this requires further investigation.
• Peak reduction of the neighbourhood profile, through the deferral of ‘wet’ appliances has a demonstrable effect. The additional benefit of peak-shaving reducing losses in more stressed networks is worth further investigation.
12.4 Further work

12.4.1 Survey work

Both the static and dynamic aspects of the models presented would benefit from improved survey data. In terms of static data, appliance ownership data is scarce. For example, the TUS only reports the presence of certain technologies, and except for televisions, multiple appliance ownership, which appears common, is not recorded. MTP appliances ownership data is not well referenced and relies on a mix of dated and confidential sources. These data could be surveyed separately but it would be important to make appropriate records of demographic data to allow matching of appliance ownership and householder’s behaviour, since these are not independent. Similarly, the actual power flow characteristic of more appliances would be valuable and improve the model diversity.

In terms of dynamic data, survey work could greatly improve the ‘behavioural diversity’ as represented by the narrative and habit definitions. This might comprise questionnaires or interviews, asking for example ‘What do you usually cook for lunch on a Sunday?’, or ‘What mood lighting do you use in Summer/Winter?’. However there may be issues relating to personal privacy that make this approach problematic, for example, people may refrain from answering, or lie, when posed questions regarding personal hygiene. This said it would be beneficial to better understand the use of, for example showers, since they are high power loads compared to other domestic appliances. This problem would be a good application for high temporal resolution metering since the high power levels used by power showers would allow showers to be readily identified amongst the other domestic loads. A more actuate mapping of real cooking habits would also be beneficial for similar reasons.

The results presented are only intended to provide proof of the frameworks capabilities. In practice to evaluate the effect of interventions, either on a house by house, neighbourhood, or on a national basis, would require more accurate survey data and agreement with regards to assumptions. In the longer term there is no reason that this approach could not be scaled up to model a whole village or town, other than the limits of the TUS dataset. In this regard, stochastic approaches could be substituted for actual data.
12.4.2 Time resolution
The model framework provides means to synthesise demand profiles at one second granularity. Whilst this resolution allows all appliances to be modelled accurately, it may be possible to lower the resolution without losing significant accuracy. This would be valuable in terms of decreasing the duration of the model execution and in turn allowing more to be run. Extending this idea, different time resolutions might be appropriate to different applications. In order to experiment with the sensitivity to time resolution to model framework could be adapted to support a range of time resolutions.

12.4.3 Micro-generation
The integration of different types of micro-generation into the models framework is envisaged as the next step for the framework as presented. While in the current framework negative impedances can be used to define, for example photovoltaic (PV) panels, they can result in negative power flow to the wider network. In practice PV systems would stop supplying power in what would be over-voltage\textsuperscript{121} conditions. The implication of this is that to support the analysis of micro-generation the frameworks method of analysing power flow would have to be elaborated. Whilst not especially complex, this would involve a multiple traversing of the model network and slow down the simulation process.

12.4.4 Evaluating carbon benefits
The value of interventions in terms of carbon emission has only been analysed using a simple time of use model, however there several alternative approaches that could be adopted. For example, demand profile data could be exported to a supply system model which uses a simplified ‘merit order’ model to dispatch different generators and thus generate carbon emission data.

However in the longer term, the value of DSM will not only be linked to the carbon intensity of the supply side. If the UK supply portfolio sees a large increase in wind powered generators, then demand response could be used to support wind capacity by replacing STOR generation. Conversely a wide adoption of nuclear generation would benefit from a flatter demand profile.

\textsuperscript{121} Where supply exceeds demand on the local network.
While demand side models could be further developed and integrated with supply side models, it would require careful consideration and the experience of developing the modelling framework presented in this thesis serves as a warning to those who embark on such a venture. In the words of Charles Babbage:

‘No person will deny that the highest degree of attainable accuracy is an object to be desired, and it is generally found that the last advances towards precision require a greater devotion of time, labour, and expense, than those which precede them.’

Charles Babbage
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