Demand Side Management: Flexible demand in the GB domestic electricity sector

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DECLARATION

This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

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Abstract

In order to meet greenhouse gas emissions targets, the Great Britain (GB) future electricity supply will include a higher fraction of non-dispatchable generation, increasing opportunities for demand side management (DSM) to maintain a supply/demand balance. Domestic electricity demand is approximately a third of total GB demand and has the potential to provide a significant demand side resource.

An optimization model of UK electricity generation has been developed with an objective function to minimize total system cost (£m/year). The models show that dispatchable output falls from 77% of total output in 2012 to 69% in 2020, 41% in 2030 and 28% in 2050, supporting the need for increased levels of future DSM.

Domestic demand has been categorised to identify flexible loads (electric space and water heating, cold appliances and wet appliances), and projected to 2030. Annual flexible demand in 2030 amounts to 64.3TWh though the amount of practically available demand varies significantly on a diurnal, weekly and seasonal basis. Daily load profiles show practically available demand on two sample days at three sample time points (05:00, 08:00 and 17:30) varies between 838MW and 6,150MW.

Access to flexible demand for DSM purposes is dependent on the active involvement of domestic consumers and/or their acceptance of appliance automation. Analysis of a major quantitative survey and qualitative workshop dataset shows that 49% of respondents don’t think very much or not at all about their electricity use. This has implications for the effectiveness of DSM measures which rely on consumers to actively modify behaviour in response to a signal. Whilst appliance automation can be a practical solution to realising demand side potential, many consumers are reluctant to allow remote access. Consumers are motivated by financial incentives though the low value of individual appliance consumption limits the effectiveness of solely financial incentives. A range of incentives would be required to encourage a wide cross-section of consumers to engage with their electricity consumption.

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Nomenclature

Abbreviations and acronyms

AES	Annual Energy Statement
AI	Artificial Intelligence
BEA	British Electricity Authority
BETTA	British Electricity Trading and Transmission Arrangements
BM	Balancing Mechanism
CCC	Committee on Climate Change
CCGT	Combined cycle gas turbines
CCS	Carbon capture and storage/sequestration
CEGB	Central Electricity Generating Board
CfD	Contract for difference
CHP	Combined heat and power
COP	Coefficient of Performance
CP	Capacity Payment
CPF	Carbon Price Floor
CPS	Carbon Price Support
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DG	Distributed Generation
DNC	Declared Net Capacity
DNO	Distribution Network Operators
DP	Dynamic Programming
DSM	Demand Side Management
DTI	Department of Trade and Industry
DUKES	Digest of United Kingdom Energy Statistics
EC	European Commission
ECCP	European Climate Change Programme
ECUK	Energy Consumption in the United Kingdom
EMR	Electricity Market Reform
EPC	Engineering, Procurement and Construction
EPS	Emissions Performance Standard
ESB	Energy Saving (light) Bulb
EST	Energy Saving Trust

ESWH	Electric Space and Water Heating
EU	European Union
EUETS	European Union Emissions Trading System
FDD	Flexible Domestic Demand
FIT	Feed in Tariff
FOAK	First of a Kind
FPN	Final Physical Notification
GB	Great Britain
GEMA	Gas and Electricity Markets Authority
GHG	Greenhouse gas
HES	Household Electricity Survey
HV	High Voltage
IP	Interior Point
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity
LCPD	Large Combustion Plant Directive
LOLP	Loss of Load Probability
LP	Linear Programming
LV	Low Voltage
MDG	Millennium Development Goals
MPP	Major Power Producers
MV	Medium Voltage
NETA	New Electricity Trading Arrangements
NLP	Nonlinear Programming
NOAK	Nth of a Kind
OFFER	Office for Electricity Regulation
OFGEM	Office for Gas and Electricity Markets
PES	Public Electricity Supply
PLF	Plant Load Factor
PPP	Pool Purchasing Price
QP	Quadratic Programming
RUP	Reference Unit Power
SLB	Standard Light Bulb
SMP	System Marginal Price

SO	System Operator
STOR	Short Term Operating Reserve
TEC	Transmission Entry Capacity
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOLL	Value of Lost Load
WANO	World Association of Nuclear Operators
WMO	World Meteorological Organization
WSSD	World Summit on Sustainable Development

Parameters

EC_t	Emissions cost per technology (£/MWh)
E_t	Electricity generated in year t
FC_t	Fixed cost per technology (£/MWh)
F_t	Fuel expenditure in year t
H_T	Index of species diversity
I_t	Investment expenditure in year t
Ln	Natural log
M_t	Operating and Maintenance expenditure in year t
N	Expected life of investment
O_t	Annual output per technology (TWh)
p_i	Proportion of total sample belonging to the i^{th} species
R	Discount rate
S	Species richness (total number of species present)
TC_t	Total cost per technology (£m/year)
UC_t	Unit cost per technology (p/kWh)
VC_t	Variable operating and maintenance costs per technology (£/MWh)

Chapter 1

Introduction

Summary:

This chapter provides a brief introduction to the thesis and the policy background driving changes to the UK electricity system. It sets out the research objectives and describes the thesis outline.

1.1 Background

UK energy policy is driven by three main objectives, namely to ensure the UK has secure, clean and affordable energy supplies [1]. This “energy trilemma” [2] is driving the UK electricity sector to reduce the amount of electricity generated by power plants fuelled by fossil fuels and increase the amount generated using low carbon technologies, such as nuclear, wind, solar PV and hydro. As a result, the current “predict and provide” generation model [3], where (mainly) large thermal, fossil fuel plants are modulated to satisfy a variable, but predictable, demand, will change to a model with a lower fraction of dispatchable (controllable) generation.

The percentage of dispatchable generation capacity (mainly from coal, gas and oil fired power stations) in 2012 accounted for 77% of the total UK generation capacity and 74% of annual output. This fraction of capacity enabled the electricity system to deliver a reliable service using dispatchable supply as a mechanism to maintain a balance between supply and demand. Nuclear capacity in 2012 accounted for 10% of capacity and 18% of annual output, and non-dispatchable renewables (from wind, hydro and solar PV resources) accounted for 13% of capacity and 7% of annual output, as shown in Figure 1.1 [4].

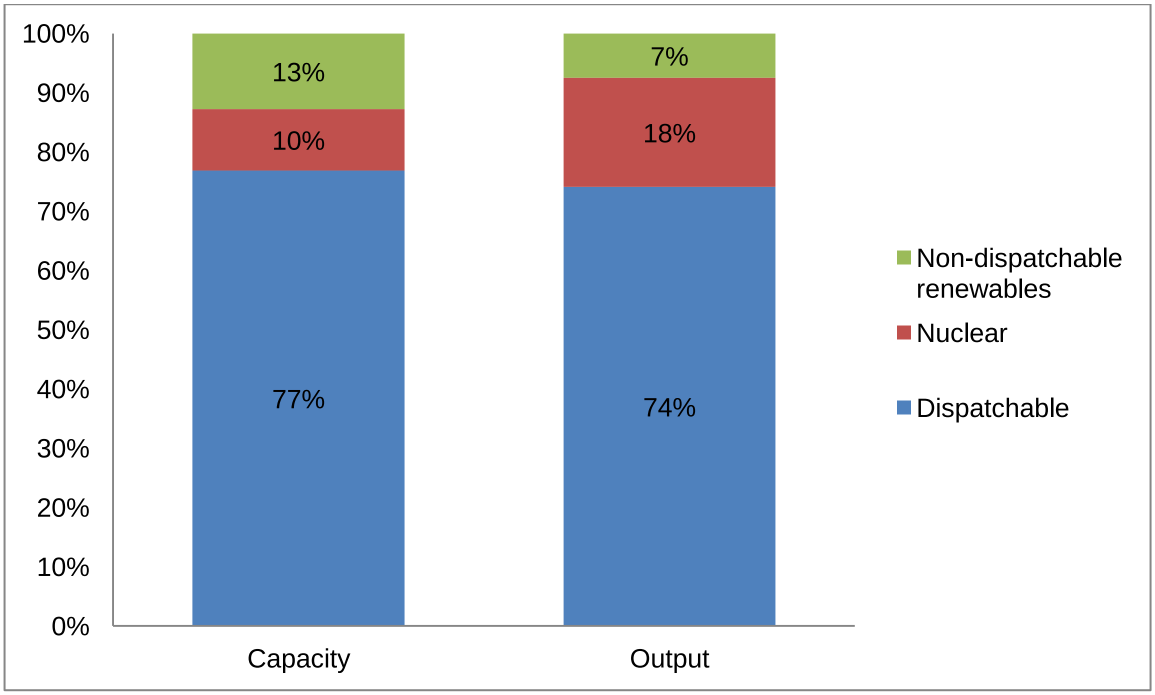


Figure 1.1 Technology share of UK generating capacity and annual output, 2012 [4]

As part of wider GHG emissions reduction targets, the UK power sector has been targeted with reducing emissions from between 443 – 559gCO_2/kWh in 2012 [5], to 300gCO_2/kWh in 2020 and 50-100gCO_2/kWh by 2030 [6]. Existing fossil fuel generating technologies currently emit approx 907gCO_2/kWh (coal) and approx 395gCO_2/kWh (CCGT) [7] and are, therefore, incompatible with meeting future emissions targets at their current level of output. In order to meet future demand for electricity, low carbon generating technologies, which are less dispatchable than fossil fuel plants, are likely to form a larger fraction of total capacity and output.

In the absence of technologies such as reliable and economically viable electricity storage and carbon capture and storage (CCS), the task of maintaining the necessary balance between electricity generation (supply) and consumption (demand) will move from a predominantly supply side function to one which will require more involvement from the demand side, particularly where intermittent generation technologies, such as wind and solar PV, forms a larger fraction of generating capacity.

UK domestic electricity demand in 2012 accounted for approx. 36% of the UK total (not including electricity consumed by the energy industry) [8], as shown in Figure 1.2, and is anticipated to increase through the wider electrification of space and water heating, and transport.

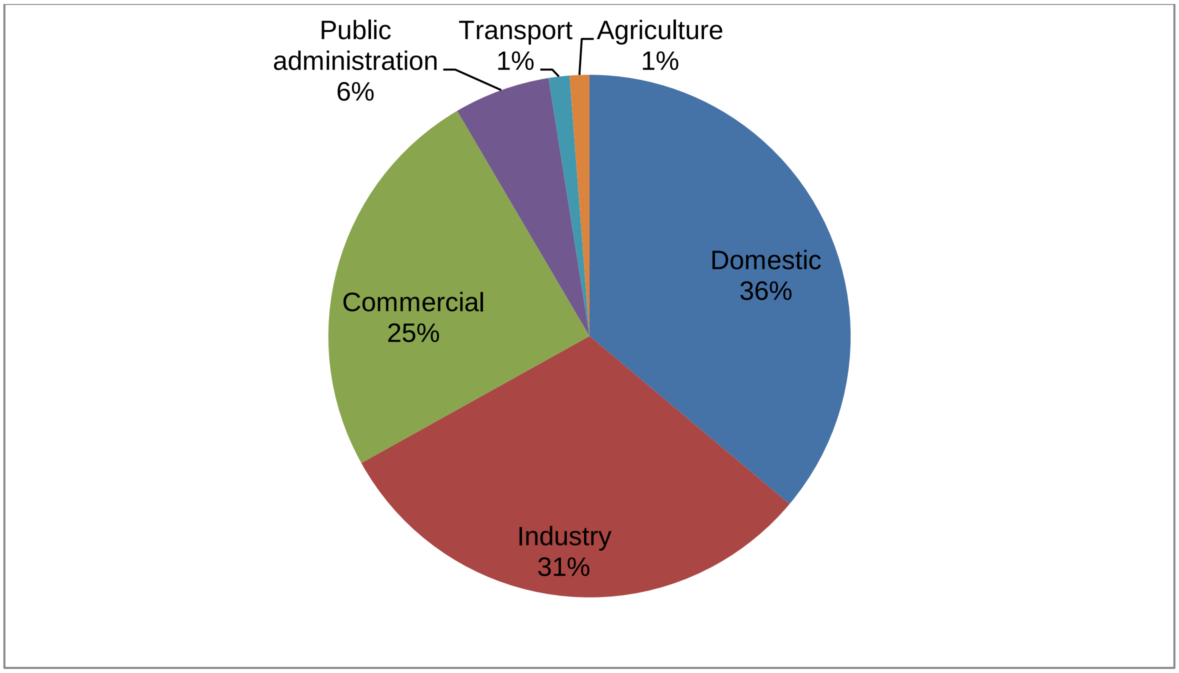


Figure 1.2 UK electricity consumption by sector, 2012 [8]

Whilst the domestic sector forms a significant part of the total demand side resource, it is widely dispersed across over 26 million households [9]. Effective access to this load presents both technological and behavioural challenges.

This thesis sets out to address the extent of GB domestic electricity demand in 2030 which can be used for demand side management (DSM) purposes, and the barriers to securing effective access.

1.2 Research objectives

The objectives of the research carried out for this thesis are:-

- to develop an understanding of the electricity generating technology components of a future electricity system which would satisfy existing, and projected, energy policy targets
- to explore the different categories of domestic electricity demand in 2030 and the extent to which this demand is flexible
- to consider the following research questions:-
    - what relationship do domestic consumers have with their electricity consumption?
    - how acceptable is appliance automation to domestic consumers?
    - what incentives would encourage domestic consumers to engage more with their electricity consumption and allow access to flexible domestic demand?

The following work has been carried out to achieve these objectives.

- An optimization model has been created to derive potential generating technology combinations within future electricity systems. The objective function is to minimize annual cost, the decision variables are technology capacity and plant load factors, and the constraints are emissions, capacity and diversity.

- Domestic electricity loads have been separated into different categories and sub-categories, and annual electricity demand has been projected to 2030 for each.
- Daily load profiles have been produced for flexible domestic demand categories i.e. electric space and water heating, cold appliances and wet appliances, and the maximum amount of flexible domestic demand available at three time points on two sample days in 2030 have been shown.
- A dataset of qualitative workshop transcripts has been coded, filtered and analysed, and responses to a quantitative survey have been analyzed to address:-
    - the relationship consumers have with their electricity consumption
    - the acceptability of appliance automation
    - incentives to allow access to flexible demand

1.3 Thesis outline

The remainder of this thesis is arranged as follows:-

Chapter 2 describes energy policy and electricity market structure.

Chapter 3 presents an Excel based, optimization model giving potential generation technology combinations for 2020, 2030 and 2050. The model provides a framework to understand the impact of changes to the generation mix, particularly the major challenge of addressing the extent of non-dispatchable generation in the future.

Chapter 4 describes the amount of domestic electricity demand in GB and provides a projection of this demand to 2030. The demand is split into different categories of appliance and consideration is given to the amount of flexible demand within the total, and the amount that is practically available within the total flexible demand. Daily load profiles for flexible demand categories are also shown.

Chapter 5 explores consumer behaviour in relationship to access to flexible domestic electricity demand, and considers the extent to which consumers engage with electricity consumption or to the energy service provided e.g. light, heat etc. It draws on the qualitative and quantitative datasets generated from the UKERC funded project “Transforming the UK Energy System: Public Values, Attitudes and Acceptability”.

Chapter 6 presents final conclusions of the thesis and summarises the main findings of the research. It also describes potential future research topics based on the work carried out.

Chapter 2

Policy and structure

Summary:

This chapter sets out the background of energy policy at International, European and UK levels, including electricity market reform. It also describes the structure of the GB electricity supply market from historic, current and future perspectives.

2.1 Energy policy

A strategic framework of energy policy exists at International, European and United Kingdom levels, with a growing consensus on developing an energy policy consistent with the concerns of different stakeholders. These include environmental concerns at local and global levels, such as localised air and water pollution, to global warming and climate change, and socio-economic factors such as poverty and equality. A successful energy policy has to address sustainability and greenhouse gas emissions, security of supply, economically acceptable energy costs, equity and ethics, the need to develop new technologies, energy efficiency, resource use and the nature and behaviour of markets and societies.

2.1.1 International

The main coordinating body addressing global energy policy is the United Nations (UN). The UN views energy in terms of environmental impact, especially global climate change, and the ability for energy policy to affect socio-economic programmes.

In 1983, the UN General Assembly set up the World Commission on Environment and Development to formulate a “global agenda for change” [1] chaired by the former Prime Minister of Norway, Gro Harlem Brundtland. The Commission reported in 1987 giving the well known “Brundtland” definition of sustainable development as development “that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1], which has wide ranging implications for a world energy sector dependant on the use of non-renewable fossil fuels as primary sources of energy.

The Intergovernmental Panel on Climate Change (IPCC) was created in 1989 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to address the international community’s growing concern over climate change. This is structured with three main working groups specialising in different aspects of climate change:-

- Working Group I (WGI) assesses the physical scientific aspects of the climate system and climate change.
- Working Group II (WGII) assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change and options for adapting to it.

- Working Group III (WGIII) assesses options for mitigating climate change including the role energy can play in achieving this ambition [2].

In 1992, the IPCC organised the UN Conference on Environment and Development (UNCED) in Rio de Janeiro. Known as the “Earth Summit”, its outcomes were the formation of the UN Commission for Sustainable Development, a programme for action entitled Agenda 21, and the creation of the United Nations Framework Convention on Climate Change (UNFCCC). This set out recommended reductions in levels of greenhouse gas (GHG) emissions with a view to stabilising atmospheric GHG “at a level that would prevent dangerous anthropogenic interference with the climate system” [2]. On the basis that 84% of GHG emissions in Annex 1 countries come from the energy sector and 60% in developing countries [3], this had significant implications for energy policy around the world. Annex 1 countries are “industrialised countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT parties) including the Russian Federation, the Baltic States and several Central and Eastern European States”[3].

Under the auspices of the UNFCCC, the Kyoto Protocol was released in 1998, following the summit held in December 1997. This set in place targets for reductions in global GHG emissions over a “first commitment period” of 2008-12. These ranged from an average reduction of 8% for EU countries to a 10% increase for Iceland against an emissions base year of 1990 [4]. Strengthening the recommendation aspect of the UNFCCC targets, under Kyoto the targets are formal commitments from the Protocol’s signatories which became legally binding in February 2005. The Doha Amendment to the Kyoto Protocol was agreed in December 2012 and covers emissions from 2013 to 2020. This is anticipated to be agreed and put into force at the Conference of the Parties (COP) to be held in Paris in December 2015 [5], and will commit the signatories to an average of 18% reduction in GHG emissions from 1990 levels [6].

The next major step taken by the UN was in 2000 at the Millennium Summit in New York. This culminated in the United Nations Millennium Declaration stating the Millennium Development Goals (MDG) of an end to poverty and hunger, universal education, gender equality, child health, maternal health, combat HIV/AIDS, environmental sustainability and global partnership [7].

The Millennium Summit, in turn, informed the agenda for the 2002 World Summit on Sustainable Development (WSSD) held in Johannesburg.

The plan of implementation from WSSD contained the following sustainable development goals in relation to energy policy:-

- improve access to reliable, affordable, economically viable, socially acceptable and environmentally sound energy services
- recognise that energy services have positive impacts on poverty eradication and the improvement of standards of living
- develop and disseminate alternative energy technologies with the aim of giving a greater share of the energy mix to renewable energy and, with a sense of urgency, substantially increase the global share of renewable energy sources
- diversify energy supply by developing advanced, cleaner, more efficient and cost effective energy technologies
- combine a range of energy technologies, including advanced and cleaner fossil fuel technologies, to meet the growing need for energy services
- accelerate the development, dissemination and deployment of affordable and cleaner energy efficiency and energy conservation technologies
- take action, where appropriate, to phase out subsidies in this area that inhibit sustainable development [8]

In response to a request by the 2002 WSSD, UN-Energy was formed in 2004 to provide a coordinated approach to energy across multiple agencies within the United Nations, principally to allow the delivery of the Millennium Development Goals.

UN-Energy is organized around three thematic clusters of:-

- energy access
- renewable energy
- energy efficiency

These clusters are each further divided into five tasks, as follows:-

- capacity building
- enabling environments
- financing
- knowledge sharing
- research, technology development and demonstration [9]

It can be seen from the above that the potential role for energy in the achievement of the United Nations' goals, such as climate change mitigation and socio-economic development, is increasingly crucial. The United Nations' role is also moving from coordinating treaties with optional targets to creating legally binding commitments requiring specific legislation to enact.

2.1.2 Europe

Since the 1950's, energy has been central to the development of post-war alliances between individual European countries (1951, European Coal and Steel Community (ECSC) and 1957, European Atomic Energy Community (Euratom)). These specific alliances have grown into the 28 State European Union in 2014, with a remit across a wide range of activities.

Energy policy has remained a crucial part of the European Union in similar terms to that of the wider international community i.e. environmental impact, especially climate change, and the socio-economic effect energy has on EU Member States.

The European Union (EU) has the world's third largest energy market and is responsible for approximately 10% of global GHG emissions [10]. More than 80% of these emissions are from energy production and use [11]. The impact on energy policy of commitments to reduce emissions is, therefore, significant.

Vulnerability studies have indicated that the impact of climate change on sea levels could affect 68 million people in the EU and that temperature increases could have a negative impact on the health of large numbers of citizens [10].

In line with international action to address the growing threat posed by climate change, the EU has progressively responded to targets set by the IPCC and UNFCCC to reduce GHG emissions and limit the extent of GHG concentrations in the atmosphere. Shortly after the IPCC's first Assessment Report in 1990, the EU undertook to stabilize CO_2 emissions at 1990 levels by 2000, a target which was achieved [11].

The EU then responded to the outcomes of the Rio Earth Summit of 1992 and the Kyoto Protocol of 1997 by committing to an average reduction of 8% in GHG emissions below 1990 levels by 2008-12, by the 15 EU Member States in existence prior to 2004 [4]. The average reduction achieved over the period 2008-12 was 11.8% [10].

The European Climate Change Programme (ECCP) was set up in 2000 to ensure GHG emission reductions were achieved. A core aspect of the ECCP was the introduction of the EU Emissions Trading System (ETS) which came into effect in 2005 and is now in its third phase, running from 2013 to 2020. Other aspects included requirements for minimum levels of energy efficiency for end-use equipment, energy demand management, expansion of combined heat and power (CHP), energy efficiency in public procurement and a communication plan to raise public awareness [12].

The follow on programme (ECCP(II)) was launched in the autumn of 2005 with a focus on carbon capture and storage technology and reducing emissions from transport.

The importance of energy policy in the EU was reinforced through the publication of a Green Paper in 2006, setting out the “European Strategy for sustainable, competitive and secure energy” [13]. This requested that Member States implement an energy policy built on the core objectives of sustainability, competitiveness and security of supply, and to deal with specific energy-related issues including growing dependence on energy imports, volatile oil and gas prices, climate change, increasing demand for energy and obstacles to a competitive internal energy market.

It also set out the following priority areas:-

- Energy for Growth & Jobs: completing the internal energy market, including:-
    - a European grid
    - priority interconnection plan
    - investment in generation capacity
    - clear-cut unbundling of generation and distribution activities
    - boosting industry competitiveness
- Security of supply: solidarity between Member States

The 2006 Green Paper was followed in 2007 with an “Energy Policy for Europe”. This committed the EU to “a low consumption economy based on more secure, more competitive and more sustainable energy. Priority energy objectives involve ensuring the smooth functioning of the internal market in energy, security of strategic supply, concrete reductions in greenhouse gas emissions caused by the production or consumption of energy and the European Union's ability to speak with a single voice on the international stage" [14].

European energy strategy now covers renewable energy, energy efficiency, technology and innovation, oil, coal, single market for gas and electricity, nuclear energy, energy from abroad, and energy infrastructure [15].

The direction of policy at a European level is, therefore, clear. There is a strong commitment to support international efforts to limit anthropogenic GHG emissions through increased energy efficiency, the development of non-fossil fuel alternatives and a focus on securing reliable future energy supplies. This direction strongly informs policy decisions made by Member States, including the United Kingdom.

2.1.3 United Kingdom

Historically, the United Kingdom exploited its fossil fuel resources to expand its economy and global influence. The industrial revolution was driven by energy generated from indigenous fossil fuel reserves which laid the foundations of the modern British economy and its position in world politics. Whilst the UK's current global influence has substantially diminished since Victorian times, hydrocarbon exploitation has continued to play an important part in the growth of its economy and in the living standards of its population.

Total income from the UK's Continental Shelf oil and gas fields (known as North Sea oil) since 1970 is in excess of £912bn at 2013 prices [16] and has generated total government revenues (excluding gas levy) of over £185bn over the same period [17].

However, peak production has now passed and although there remains an estimated maximum of 1,084 million tonnes of oil [18] and 650bn cubic metres of gas [19], compared with cumulative production of 3,583 million tonnes of oil at the end of 2013 and 2,451bcm of gas at the end of 2012, this will form a declining part of the UK's energy mix and economic prosperity in the future.

The increasing awareness of the impact anthropogenic GHG emissions have on climate change has had an effect on the UK Government's approach to energy policy. This has been partly driven by initiatives at international and European levels and shares the same key drivers of environmental impacts and socio-economic effects.

The EU response to the 1997 Kyoto Protocol, where it committed to an average reduction of 8% in GHG emissions below 1990 levels by 2008 [12], translated to a target reduction of 12.5% for the UK [20]. The Doha amendment to the Kyoto Protocol, covering emissions from 2013 to 2020, will result in the UK being targeted to reduce its emissions by 2.743bn tonnes CO_{2equ} [21]. As energy supply and energy use (excluding transport) accounted for 63.8% of all UK GHG emissions in 2009 [20] the Kyoto Protocol acted as a catalyst for energy policy activity in the UK.

In July 2006, the Department of Trade and Industry (DTI) published "The Energy Challenge, Energy Review Report 2006" [22] which set out the Government's energy policy goals, summarised as:-

- cut CO_2 emissions by 60% by 2050 with real progress by 2020
- maintain reliability of energy supplies
- promote competitive markets
- ensure every home is adequately and affordably heated

This was followed in May 2007 by the Energy White Paper "Meeting the Energy Challenge" [23] which built on the energy policy goals set out in the 2006 Energy Review and proposed a strategy to:-

- save energy
- develop cleaner energy supplies
- secure reliable energy supplies at prices set in competitive markets

The Climate Change Act, 2008 [24], introduced a legally binding target of 80% reduction in GHG emissions by 2050 and 34% reduction by 2020 against 1990 levels. The 2008 Energy Act [25] was also introduced which put in place the legislative instrument to allow the 2007 Energy White Paper to be enacted.

2008 also saw the creation of the Department of Energy and Climate Change (DECC) to replace the Department for Business Enterprise and Regulatory Reform (BERR) for energy and the Department for Environment, Food and Rural Affairs (Defra) for climate change. This signified recognition by the UK Government that environmental concerns are closely linked to energy policy.

The arrival of the Coalition Government in May 2010 brought a number of changes to energy policy in the UK with Prime Minister David Cameron predicting the government would be “the greenest government ever” [26].

One initiative under the new regime was a commitment to produce an Annual Energy Statement (AES) to provide market direction, set strategic energy policy and help guide investment. The first AES was submitted to parliament on 27 June 2010 and was organized into the following sections:-

- saving energy through the Green Deal and supporting vulnerable consumers
- delivering secure energy on the way to a low carbon energy future
- managing our energy legacy responsibly and cost-effectively
- driving ambitious action on climate change at home and abroad [27]

The government also issued the Energy Act, 2011, which has three principal objectives:-

- tackling barriers to investment in energy efficiency
- enhancing energy security
- enabling investment in low carbon energy supplies [28]

This has been subsequently superseded by the Energy Act 2013, whose main provisions include decarbonisation, stating that 2030 targets for electricity sector emissions will be set in 2016, and electricity market reform [29].

2.1.3.1 Electricity Market Reform

UK Energy Policy has three main elements:-

- security of supply
- affordability
- emissions reductions

Existing market arrangements are driven by the commercial fundamentals of dispatchable, fossil fuel generation which, unabated, is incompatible with the need to decarbonise the electricity generation sector.

The dominant investment model and risk profile is based on the wholesale price of electricity tracking fossil fuel prices which helps to protect the generator's margin. Renewable and low carbon generation technologies have different cost profiles to fossil fuel plants especially gas. CCGT plants have a low capital cost and high operating costs which are predominantly made up of the cost of fuel. Renewable and low carbon generation (including nuclear) have relatively high capital costs and low operating costs which are not linked to fossil fuel prices and, therefore, the wholesale electricity market.

25% of existing generation capacity will need to be replaced by 2020 due to the requirements of the Large Combustion Plant Directive (LCPD) and scheduled nuclear, and other, plant retirals [30].

£110bn investment is required in the UK by 2020 (£75bn new electricity generation and £35bn in transmission and distribution) which is twice the current level of investment (the "big 6" energy companies, i.e. British Gas/Centrica, E.ON (formerly PowerGen), Npower (RWE), EDF Energy, Scottish Power (Iberdrola) and Scottish and Southern Energy, currently spend approx £5bn pa). This is in the face of strong international competition for infrastructure investment with the IEA estimating global energy infrastructure investment required of $48tr to 2035 [31].

25% of the world's power stations will be over 40 years old by 2015 [32], competition from other infrastructure investment requirements, such as the estimated $309bn required by Japan to rebuild its infrastructure following the 2011 earthquake and tsunami, and the financial crises affecting Europe, United States and other countries, all put pressure on policy makers to take steps to make the UK more attractive to pension funds and other institutional investors. This is particularly so given the extent to which these investors are already exposed to sterling denominated infrastructure investments such as the £70bn of PFI investments in place.

Other drivers for UK policy include the prediction that demand and cost for electricity is likely to increase, fossil fuel prices are expected to rise and become increasingly prone to supply scarcity issues, and the "big 6" domination of the market raising competition concerns.

The Government's response to these challenges is to reform the electricity market to reduce the risk of low carbon and renewable investments and to make them more attractive. The objectives of the reform are to deliver:-

- secure, low-carbon and affordable electricity
- flexible, smart and responsive system
- diverse and secure range of low carbon sources
- full part played by demand management, storage and interconnection
- competition between low-carbon technologies
- network capable of satisfying increased demand, especially from electric vehicles and electric heating
- least cost to consumers

There are four main areas within the reforms:-

- Emissions Performance Standard (EPS)
- Carbon Price Support
- Feed-in-Tariffs (FiT) with Contracts for Difference (CfD)
- Capacity market (including demand side engagement)

Emissions Performance Standard (EPS)

The EPS sets a maximum limit on the allowable emissions from generating plant. The 2013 Energy Act sets a level of 450gCO_2/kWh which allows CCGT generation plant to continue but would exclude unabated coal fired stations [29].

Carbon Price Support

This element of Electricity Market Reform is led by HM Treasury, and not DECC, and involves an additional carbon levy outside of the EUETS. The HM Treasury consultation ended on 11 February 2011, earlier than the rest of the EMR consultations, in order to be incorporated within the budget on 24 March 2011, which announced a Carbon Price Floor of £16/tCO2 to be introduced on 1 April 2013. The Carbon Price Support (CPS) commences at £4.94/tCO_2 and is in addition to the EUETS rate, with an intention to escalate to 2020. The target price floor of £16/tCO_2 in 2013 is to rise to £30/tCO_2 by 2020 and is projected to reach £70/tCO_2 by 2030. The 2014 budget confirmed the CPS rate will be capped at a maximum of £18/tCO_2 until 2019-20 [33]. The CPS is the UK-only levy added to the cost of carbon under the EUETS, and has been capped to reduce the potentially damaging impact to UK based companies exposed to higher energy costs than those elsewhere in Europe.

The additional cost of the CPS results in a higher cost of fossil fuel generation, which remains as the electricity wholesale price setting technology. This will increase the wholesale price and reduce the subsidy required for low carbon generation.

Feed in Tariffs (FiT)

The objective of the feed-in-tariff is to encourage investment in low carbon generating technologies by providing a greater level of certainty of future earnings. The initial consultation offered a preferred option of a FiT with contracts for difference (CfD) with a second preference for a Premium FiT. A CfD FiT is based on the difference between the average wholesale price ("reference price") and a pre-agreed fixed level ("strike price"). The Premium FiT pays a premium to the low carbon generator above the wholesale price. A Fixed FiT sets a fixed price for low carbon generation irrespective of the wholesale price.

The 2013 Energy Act opts for a FiT with CfD in order to maintain an incentive for the low carbon generators to time their sales into the market to achieve rates above the reference price. The principle of the CfD is that it allows for repayment when the reference price is above the strike price.

The proposals recognise that different generation technologies (i.e. intermittent – wind, wave and solar; baseload – nuclear and some biomass and CCS; and flexible – fossil fuel plant and some biomass and CCS) require different support structures and incentives.

Capacity Market

The objective of the Capacity Market is to ensure future security of supply and to maintain capacity margins. Resource adequacy is addressed and not short term operational security (e.g. Short Term Operating Reserve (STOR)) which remains the responsibility of National Grid. The Capacity Market element within EMR will provide "payment for reliable sources of capacity to encourage the investment needed to replace older power stations and provide backup for more intermittent and inflexible low carbon generation sources", and will also "support the development of more active demand management in the electricity market" [34].

2.2 Structure of GB electricity supply sector

2.2.1 Historic

The UK Electricity Market defines the relationship between the different parties in the electricity system including generators, transmission and distribution network operators, retailers, consumers, investors, government and regulators.

The UK Government's objective is for the market to deliver "secure, affordable and low-carbon energy supplies" [35], though other actors' legitimate objectives may be prioritised differently. Institutional investors, for example, may require a market which delivers predictable, long-term returns, and commercial undertakings may have other fiduciary obligations to shareholders which supplant those of Government. This highlights an area of tension for Government policy which on the one hand favours a market led approach to the sector whilst, on the other hand, recognising its strategic importance in delivering a "public good" [36].

The development of the UK electricity market can be described in four broad time categories:-

- pre 1990
- 1990 – 2001
- 2001 – 2005
- 2005 – present

Pre 1990

In 1881 the UK's first commercially provided public electricity supply was offered in Godalming, Surrey. This was followed by other towns in an uncoordinated expansion across the country.

In 1919 the Electricity Supply Act established Electricity Commissioners and in 1926 the Electricity (Supply) Act created the Central Electricity Board which set up 132kV transmission system linking local distribution networks across the country. In 1945, 240V became standard and, in 1947, the full grid was completed and frequency standardized at 50Hz, 66 years after Godalming.

Following the Second World War, the prevailing political philosophy was one of central control over the economy. This manifested itself in 1948 when the electricity supply industry was nationalised and the British Electricity Authority (BEA), along with 14 area Electricity Boards, were formed.

In 1957 the BEA was replaced in England and Wales by the Central Electricity Generating Board (CEGB). This took responsibility for generation and transmission, through the National Grid, to 12 Area Electricity Boards. The South of Scotland Electricity Board (SSEB) took over BEA's functions in the South of Scotland. Electricity in the Highlands and Islands had been run by North of Scotland Hydro-Electric since 1943.

1990 – 2001

The next major change to the electricity market came in 1989 with the introduction of the Electricity Act. This privatised the electricity system and introduced competition, reflecting the political belief in free markets and “de-nationalisation” under the Conservative, “Thatcher” Government. The Act was implemented in April 1990 and made the following changes:-

- Area Boards became Public Electricity Supply Companies (PES)
- National Grid and pumped storage stations transferred to National Grid Company
- CEGB's fossil fuel stations split between National Power and PowerGen
- Nuclear stations transferred to Nuclear Electric
- SSEB's two nuclear stations transferred to Scottish Nuclear
- Scottish Power and Scottish and Southern Energy created

In 1997 the Office for Electricity Regulation (OFFER) carried out a Review of Electricity Trading Arrangements (RETA) and in 1999 OFFER was merged with OFGAS to form the Office for Gas and Electricity Markets (OFGEM). In 2000 the consumer watchdog functions of OFGEM were transferred to Energy Watch (subsequently disbanded in 2008).

The trading arrangements during this period involved the use of an electricity “pool” in which generators bid into the pool the quantity and price of electricity they would supply, through a day ahead auction. This operated as a commodity spot market, producing the reference price, and as a balancing market.

The demand was forecast and generators graded on a price basis until the forecast demand was met. All “in-merit” generators, i.e. those bidding at or below the maximum price for electricity required to satisfy the forecast demand, were paid the same price, the System Marginal Price (SMP), irrespective of their bids. This is classed as a uniform-price auction.

A capacity mechanism was also created whereby generators were paid for declared available generation capacity. The cost of this was added to the SMP to give a Pool Purchase Price (PPP). The Capacity Payment was calculated using the following equation:-

$CP = (VOLL – SMP) \times LOLP$

CP= Capacity Payment
VOLL = Value of Lost Load
SMP = System Marginal Price
LOLP = Loss of Load Probability

This resulted in an increased payment when the predicted system demand approached the available generation capacity. Ancillary charges were added to the PPP to arrive at the Pool Selling Price (PSP) which suppliers paid for electricity to sell on to consumers through the retail market.

During this period the market was dominated by the two major generators, National Power and PowerGen, who effectively set the SMP. Price-cost margins increased and the capacity payment mechanism manipulated in favour of the generators. The market design favoured the horizontally integrated business model, across the chain. The Scottish design was based on a vertically integrated model which did not involve bidding into a pool. Whilst electricity pricing was linked to the English market, Scottish retail prices were still higher than that in England and Wales.

Other limitations of the “pool” system were that it involved only generator side bidding and no bidding from the demand side, limited competition on the retail side and costs of non-optimal dispatch borne by the consumer.

2001 – 2005

2001 saw the introduction of the New Electricity Trading Arrangements (NETA) with a move to bilateral trading between generators and suppliers. This incorporated a series of forward markets and a short term balancing market with both generation and demand side bidding. The generators stated how much they would supply and at what price and the suppliers stated how much they wanted to purchase and at what price.

More than 95% of electricity was traded outside of the Balancing Mechanism (BM) with the System Operator (SO), National Grid, having responsibility for maintaining system balance though not being involved in the bilateral agreements. Balancing mechanism units could be a single generating set or a large customer/several smaller customers.

The Final Physical Notification (FPN) of each BM unit had to be declared one hour before the start of the actual half hour period ("gate closure"). The SO maintained system balance by requesting BM units vary their FPN by either an offer to increase the amount of electricity in the system or bid to reduce the amount of electricity in the system. This avoided the need to make capacity payments for spare generating capacity.

The design of the system favoured suppliers and encouraged vertical integration between generators and suppliers.

Other legislative activity during this period included the 2001 EU Large Combustion Plant Directive, which aims to reduce the emissions of SO_2, NO_x and particulate matter (PM) and will result in the closure of large emitting coal plants by 2016, the 2002 Renewables Obligation (RO), requiring suppliers to provide an increasing amount of electricity from renewable sources each year, and the 2005 European Emissions Trading System (ETS), which places a price on carbon emissions and creates a traded market for these emissions. Each of these pieces of legislation mirrors the rising importance of emissions and climate change within the policy agenda.

2005 – Present

In 2005 the NETA was replaced by the British Electricity Trading and Transmission Arrangements (BETTA). This follows many of the principles of NETA but also includes Scotland. Other changes include the consolidation of the separate transmission systems operated by National Grid, in England and Wales, Scottish Power, in the South of Scotland, and Scottish Hydro, in the North of Scotland. There is now a single transmission system operated by National Grid, with responsibility as the GB System Operator, and the three companies acting as licence holders.

Other legislative activity, including those as set out in section 2.1 above, and the 2009 European Renewables Directive, requiring 15% of all UK energy to be derived from renewable sources by 2020, the 2009 UK Renewable Energy Strategy, targeting 30% of all electricity to be derived from renewable sources by 2020, 12% heat and 10% transport, and the 2009 UK Low Carbon Transition Plan, requiring 40% of electricity to be derived from low carbon sources by 2020, all have a significant impact on the electricity market.

The switch from the electricity pool model, which favoured horizontal integration, to the bilateral trading arrangements of NETA and BETTA, favouring vertical integration, has led to the increasing dominance of the “Big 6” energy companies. These companies operate in both the generation and supply markets and supply over 99% of electricity to the UK domestic sector.

The power of the “Big 6” has led to regulatory concerns over the lack of transparency in pricing and lack of liquidity with the potential for predatory pricing and anti-competitive barriers to entry for independent generators and suppliers. The behaviour of the “big 6” is commercially rational given the market rules in which they operate but highlights the tension between a de-regulated market approach and the need to maintain a strategically important, public good service.

Changes over time within the electricity sector reflect the political and economic orthodoxy of the period. The fledgling industry was nationalised under the post-war Labour Government in 1948. The CEGB was created by the 1957 Conservative Government and privatisation (“de-nationalisation”) under the (Thatcher) Conservative Government in 1990. NETA was introduced under a (“New”) Labour Government in 2001, in a pragmatic attempt to reduce market power and the manipulation of the market by dominant market participants. Whilst this is logical, the timeframes between political tenure (relatively short) and infrastructure investment (relatively long) can create a disjointed approach to the sector.

Also seen more recently is the growing impact of climate change concerns and the drive to reduce greenhouse gas emissions, as well as the increasing influence of European legislation.

2.2.2 Current

The UK's electricity generating, transmission, distribution, supply and regulatory system is designed to deliver sufficient electricity through high, medium and low voltage (HV, MV and LV) networks across the country to satisfy consumer demand as it occurs, as shown on Figure 2.1 [37].

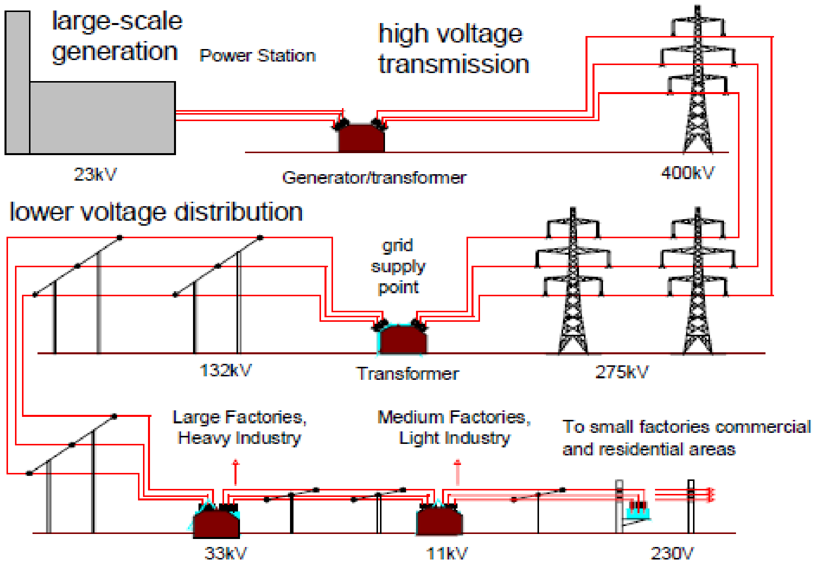


Figure 2.1 An Interconnected Electricity System [37]

The existing supply side structure can be split into the following main headings:-

- generation
- transmission and distribution
- suppliers
- regulation

Generation

In 2012, the total electricity generated in the UK (including pumped storage) was 364TWh, 90% of which was from major power producers (MPP) [38], of which, 36% was consumed by the domestic sector. The majority of this electricity was generated by coal (37%), gas (27%) and nuclear (17%), with renewables, including hydro, wind and solar PV, contributing 12% as shown on Figure 2.2.

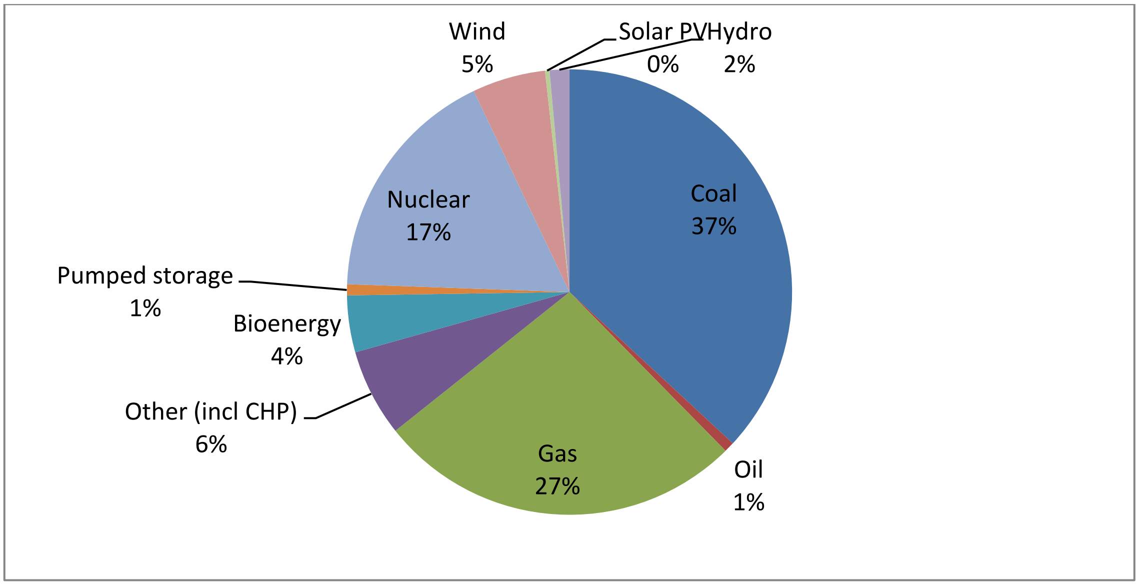


Figure 2.2 UK electricity generation output, 2012 [38]

The historical mix of fuels used for electricity generation has changed from one dominated by coal in the mid 20th century, to the expansion of gas, following the relaxation of legislation banning the use of gas to generate electricity in the 1990's, and the growth of nuclear and renewable sources. This is shown graphically on Figure 2.3 [39].

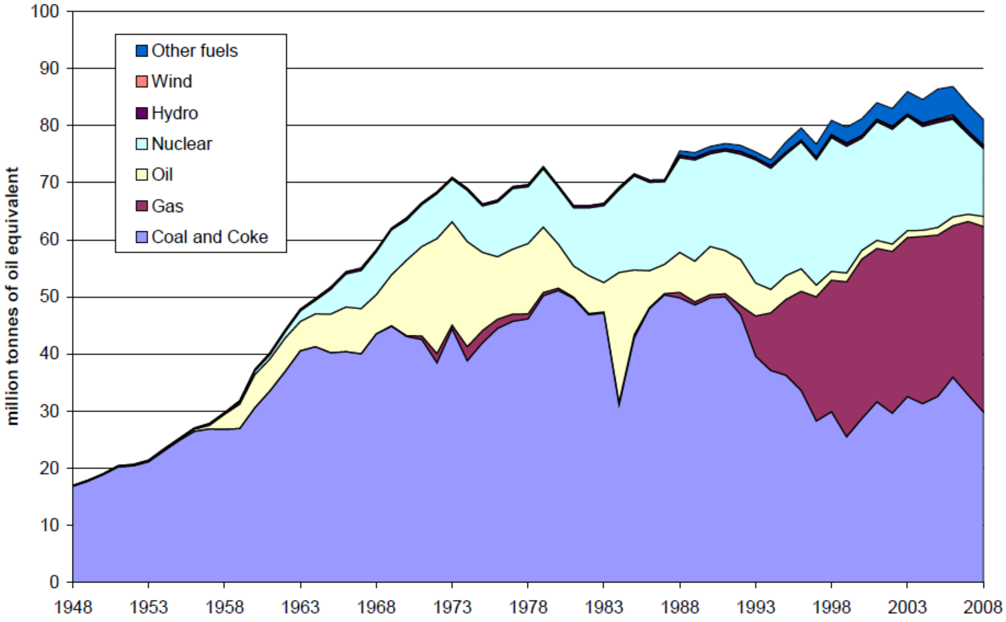


Figure 2.3 Fuels used to generate electricity 1948 to 2008 [39]

The future mix of fuels used to generate electricity is uncertain with a number of different scenarios produced depending on, amongst other factors, price of fossil fuels and carbon, availability of investment funding, and overall demand projections. Notwithstanding this uncertainty, in order for the UK to meet its targets for GHG emission reductions, the amount of electricity produced from renewable sources is likely to significantly increase over the next 10 – 20 years.

The impact on the generating structure within the UK is likely to be a move away from large, centralised power stations to smaller, distributed stations. This reverses the trend of the past 60 years which saw 92% of the installed capacity in 99% of all power stations below 400MW in 1949 changing to 95% of installed capacity in 50% of all stations above 400MW in 2009.

National Grid forecast that between 2010/11 and 2016/17 over 1/3rd of new capacity added (39.9 GW) will be from wind (11.7 GW) and other renewables (1.7 GW). This trend is forecast to continue up to 2025 when of all new capacity added (77.0 GW), 25% will be from wind (16.3 GW) and 3.5% from other renewables (2.7 GW) [40].

The UK electricity industry was privatised in 1990 following the introduction of the Electricity Act 1989 and at the end of 2013 there were 36 major power producers operating a range of different power stations throughout the UK [41]. The generators sell their electricity to suppliers, under the British Electricity Trading and Transmission Arrangements (BETTA), who then sell it to domestic, commercial and other end users.

Transmission and Distribution

Transmission of electricity over large distances is through the High Voltage (HV) network of cables operated by National Grid. Voltage levels are at 400kV and 275kV (132kV and above for offshore wind and Scotland) which reduces loss of energy over the extensive HV network. The transmission system as at 31 December 2009, which extends to approx 25,000km of HV overhead lines [42], is as shown on Figure 2.4 [43].

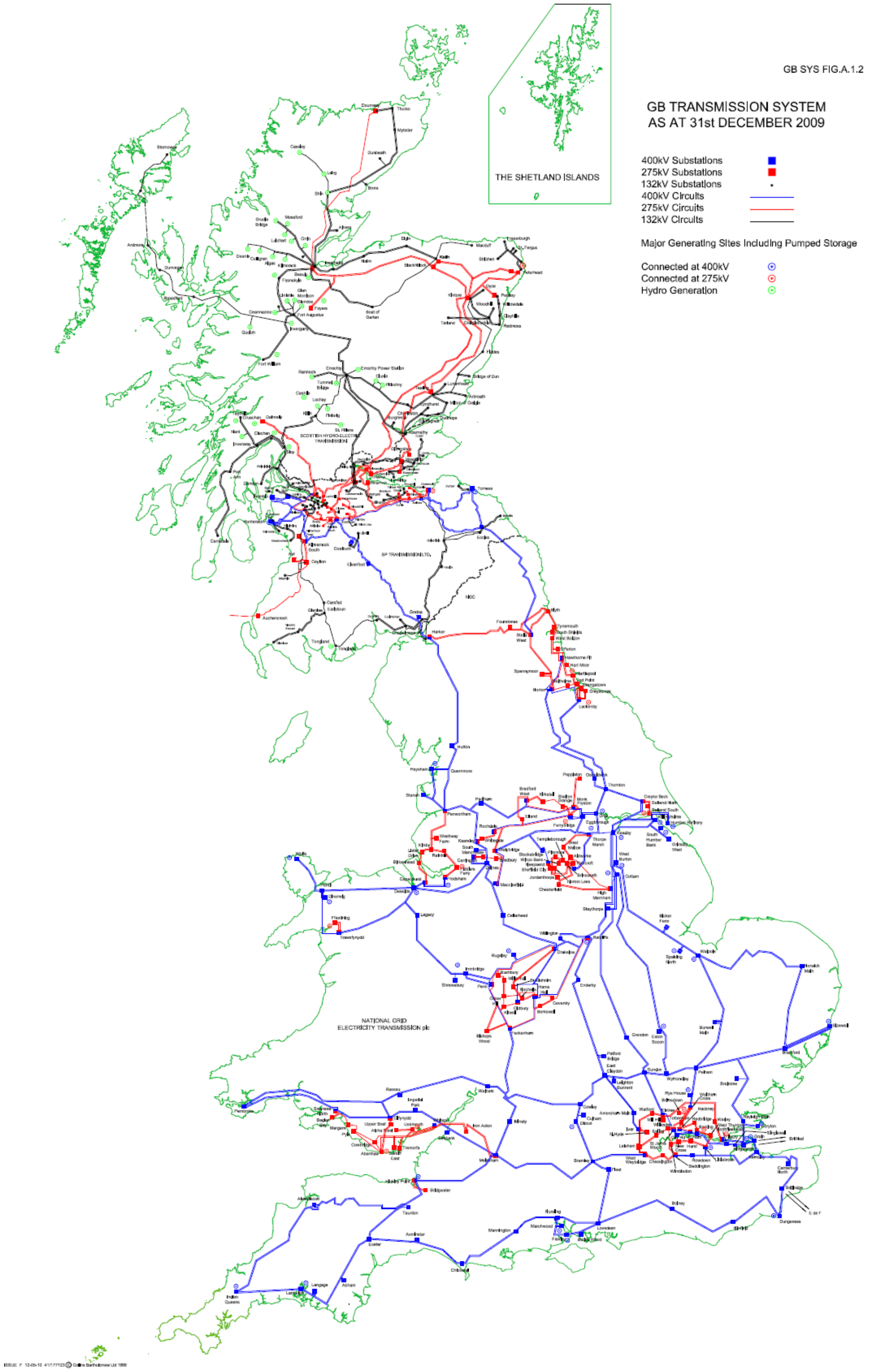


Figure 2.4 GB Transmission System 2009 [43]

Under the 1989 Electricity Act, National Grid has responsibilities including:-

- the development and maintenance of an efficient, coordinated and economic transmission system
- facilitation of competition in electricity supply and generation
- preservation of amenity
- care for the environment

With the exception of a small number of large industrial consumers, the delivery of electricity continues through medium and low voltage networks operating between 132kV and 230V, to the final consumer.

In 2014 there were 14 distribution networks owned and operated by 7 Distribution Network Operators (DNOs) in the UK. These are shown graphically on Figure 2.5.

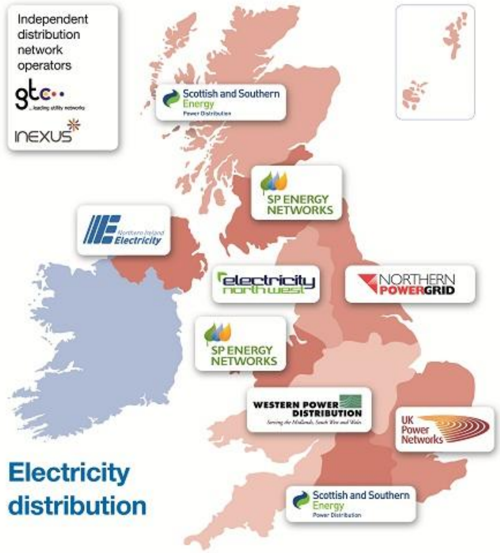


Figure 2.5 UK Distribution Network Operators [44]

DECC's 2050 Pathways Analysis [45] indicates that networks would be capable of dealing with a doubling of current levels of demand to over 800TWh pa, though changes in the nature of generation, including the impact of distributed generation (DG), would present challenges to the system, as shown on Figure 2.6 [37], as well as to the System Operator, National Grid, in its efforts to manage the instantaneous supply/demand balance through the management of frequency.

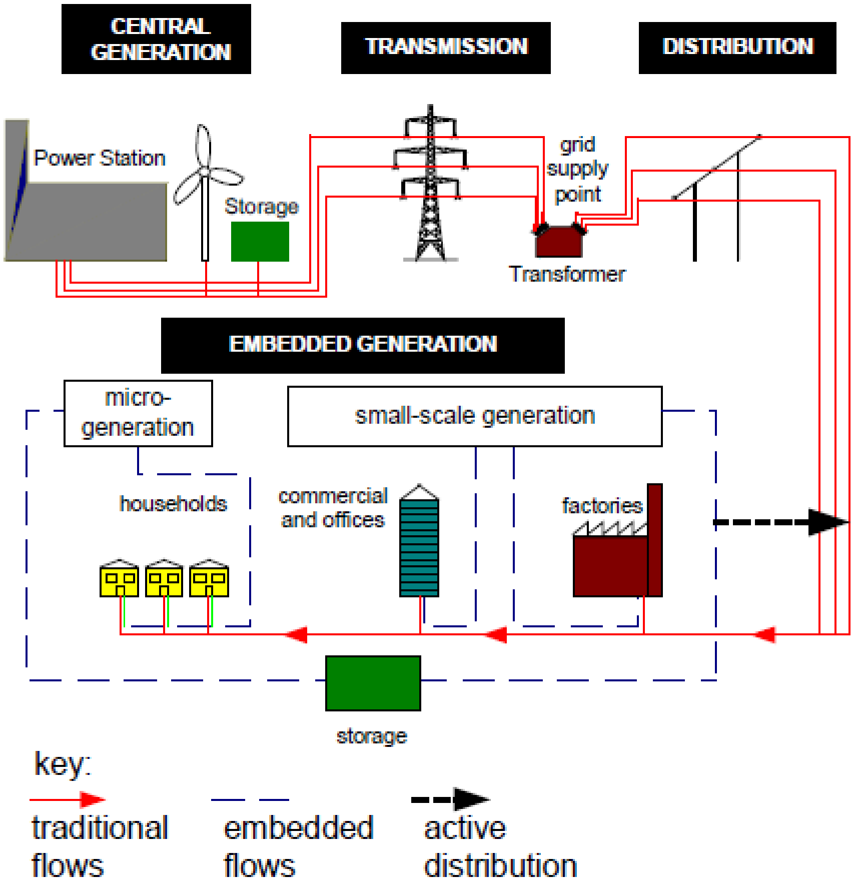


Figure 2.6 Distributed electricity system [37]

Future supply/demand balancing will also be impacted by the existing interconnectors between the UK and Ireland and France, the planned interconnector with the Netherlands, proposals for an offshore North Sea Grid connecting the UK, Holland and Germany, as well as developments of a European "supergrid".

Suppliers

Suppliers purchase electricity from the generators, through BETTA, and sell on to the final consumers. Suppliers are usually the visible element of the electricity supply chain as far as domestic consumers are concerned. Suppliers operate the meters within the home and have communications through billing, and other, notices. Suppliers will also be responsible for installing over 47 million "smart meters" in the UK before 2020.

Regulation

Regulation of the UK Electricity System is the responsibility of the Gas and Electricity Markets Authority whose powers and duties are prescribed in the Gas Act 1986, the Electricity Act 1989, the Competition Act 1998, the Utilities Act 2000, and the Enterprise Act 2002 [46].

The Authority sets policy and directs the Office of the Gas and Electricity Markets (Ofgem) with two main areas of activity. The first is the central regulatory function and the second, under Ofgem E-Serve i.e. E for Environment, Energy and Efficiency, is for Ofgem’s support and delivery functions including the smart meter roll-out programme.

2.2.3 Future

The historic and current system structure is based on large dispatchable central generators feeding dispersed loads through transmission and distribution networks. With the predicted increase in intermittent renewable generating technologies, such as wind and solar, in locations at the edge of the system e.g. off-shore wind farms, this model is likely to change. Increased small scale and microgeneration plants will also challenge the existing market practices.

Chapter 3

Generating technology mix optimization

Summary:

This chapter describes how changes in the UK's generation mix, necessary for the UK to meet its emissions targets, will result in a higher fraction of non-dispatchable, renewable generators. It gives a brief review of scenarios and optimization techniques, and introduces an optimization model which produces optimized UK generating technology mixes for 2020, 2030 and 2050.

It is based on a paper presented to the Research Students' Conference on Domestic Energy Use and CO_2 *Emissions in Existing Dwellings at Bath University on 28 June 2011, entitled* "Future UK Generation Mix and Domestic Electricity Consumption" *(Drysdale B, Bagdanavicius A, (2011))*

3.1 Introduction

The UK's electricity supply in 2012 was delivered through a predominately centralised system dominated by large fossil fuelled thermal plants supported by a significant minority of nuclear plants, and a growing amount of renewable generation, such as wind and solar, as shown in Figure 3.1.

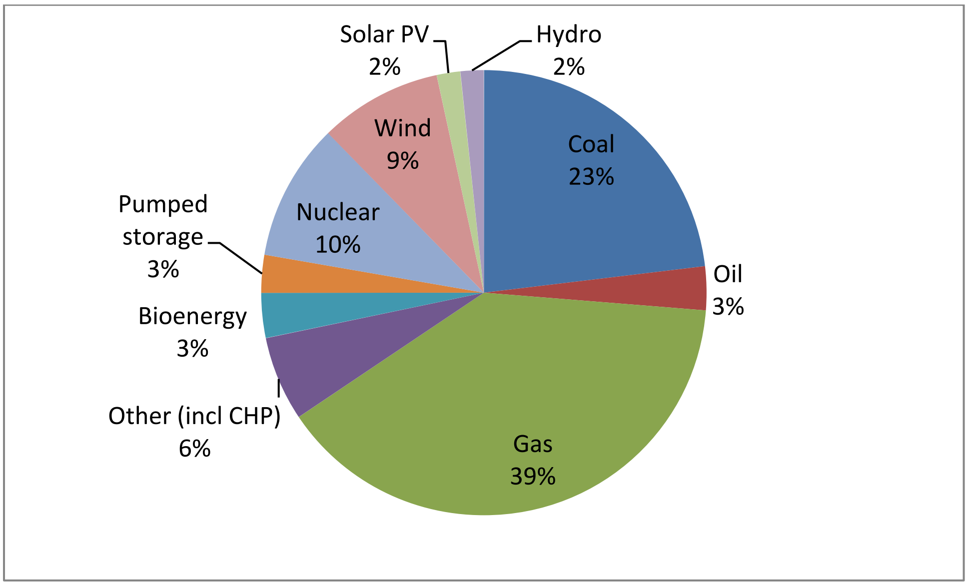


Figure 3.1 UK generating capacity, 2012 [1]

Coal, oil, gas, other and pumped storage generating capacity are expressed in terms of total transmission entry capacity (TEC), which is the generator's maximum allowed export capacity into the transmission system under the GB Grid Code [1]. Nuclear generating capacity is expressed in terms of reference unit power (RUP), which is the maximum power that can be maintained continuously throughout a prolonged period of operation under reference ambient conditions [2], as recommended by the World Association of Nuclear Operators (WANO). Bioenergy, wind, solar PV and hydro are expressed in terms of installed capacity, which is the maximum rated output power of a generator.

An alternative way of expressing renewable technology capacity is through declared net capacity (DNC) where the maximum power available is discounted to take account of the intermittent nature of the primary energy source. DUKES apply a factor of 0.43 for wind, 0.365 for small hydro, and 0.17 for solar PV [1]. This study uses installed capacities for renewable generators.

The combination of generating technologies in 2012 is flexible with sufficient control to increase and decrease output to match a variable, but predictable, demand.

The ratio of generating capacity and electricity produced by each technology varies, depending on technological, commercial and regulatory factors. For example, whilst coal plants accounted for 23% of capacity, and gas 39%, the percentage of total electricity produced in 2012 was 37% from coal and 27% from gas, as shown in Figure 3.2. The proportionally higher amount of electricity generated from coal fired power plants compared with gas plants, was due to the relatively low cost of coal compared with natural gas during the period [3]. This made it commercially advantageous to operate coal fired power plants in preference to gas fired power plants.

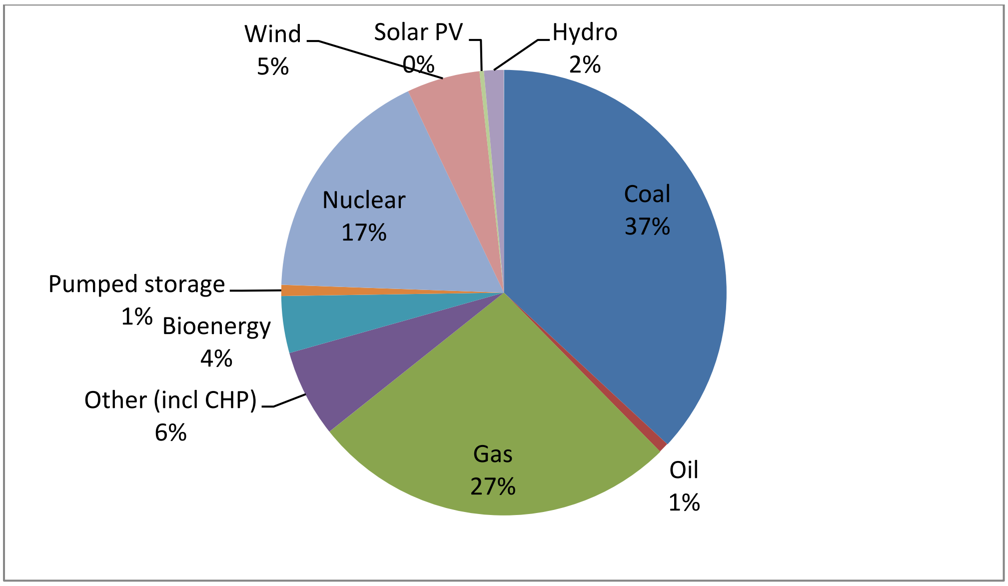


Figure 3.2 UK generation output, 2012 [1]

The plant load factor (PLF) is the average hourly quantity of electricity supplied during the year, expressed as a percentage of the average output capability at the beginning and end of the year [4], and can be established using equation {1}.

$$\mathrm{PLF}(\%) = \frac{\text{annual generation (MWh)}}{\text{plant capacity (MW)}} \times \frac{100}{8760} \qquad \{1\}$$

The plant load factors for each generating technology in 2012 are shown in Figure 3.3.

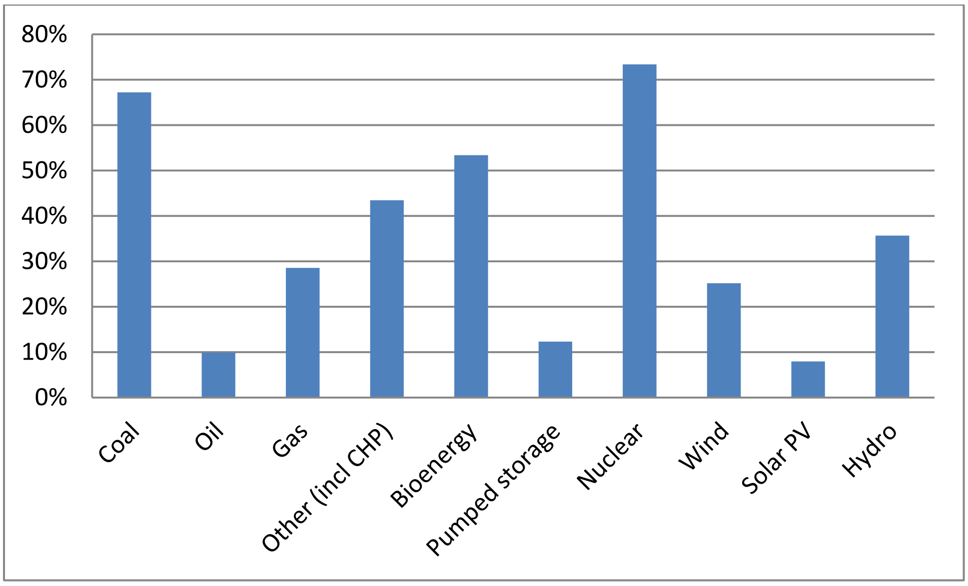


Figure 3.3 UK plant load factors 2012

Energy policy, partly driven by climate change concerns, is leading to an increased fraction of low carbon generation. This can be defined as renewable generation, such as wind and solar; nuclear; and fossil fuel generation with carbon capture and storage (CCS) technology. These are less dispatchable than traditional fossil fuel plants and create challenges in maintaining a balance between supply and demand.

3.2 Review of scenarios

Scenarios describing different future generating technology combinations are useful in considering the impact on the overall electricity system.

There are many definitions of scenarios including from the IPCC's Special Report on Emissions Scenarios (SRES) (2000) [5]. This defines a scenario as a "plausible description of how the future might develop based on a coherent and internally consistent set of assumptions (scenario logic) about key relationships and driving forces"

SETAC – Europe LCA Working Group "Scenario Development in LCA" [6] includes three basic concepts in their definition of a scenario, namely:-

- definition of alternative future circumstances
- path from present to future
- inclusion of uncertainty

Personan et al condense these concepts into the definition of a scenario as "a description of a possible future situation .... based on specific assumptions about the future, and (where relevant) also including the presentation of the development from the present to the future" [7].

The discipline of futures thinking has been employed for many centuries to consider different futures as a means to aid the development of appropriate strategies and policies [8]. One of the earliest advocates of the use of scenarios in modern times was Herman Kahn who utilized the technique to "think the unthinkable" in 1962 [8]. This was followed by other practitioners including Royal Dutch Shell who use the Global Business Network (GBN) matrix approach popularised by Peter Schwartz in 1991 [9].

Different scenarios can be established under the classifications of probable, possible and preferable [10] with predictive (probable) scenarios designed to consider what will happen, exploratory (possible) scenarios to consider what can happen, and normative scenarios to consider how a specific (preferable) target could be reached [11].

The definition of a scenario varies depending on the classification and objective of the study, and different techniques can be employed to generate different scenarios.

An overview of the techniques carried out by Bishop et al [12] identifies eight different categories of techniques, including a number of variations, as shown in Table 3.1.

Table 3.1 Categories of techniques used in scenario development (adapted from [12])

	Technique	**Variations**	**Description**	**Advantages**	**Disadvantages**
1	Judgement	- genius forecasting - visualisation - role playing - Coates & Jarratt	Relies on judgement of futurist to describe future	Easy and taps into intuitive understandings	Difficult to do well and lacks transparency
2	Baseline/ expected	- trend extrapolation - Manoa - systems scenarios - trend impact analysis	Produces one, expected, baseline future forming the basis of alternative scenarios	Easy for audiences to accept as it forms the expected outcome	No alternative scenario proposed and often discounted by futurists ("the most likely future isn't" – Herman Kahn)
3	Elaboration of fixed scenarios	- incasting - SRI matrix	Given futures (kernels) elaborated on	Easy for participation as kernels already prepared	Kernels may not be perceived as relevant

4	Event sequences	- probability trees - sociovision - divergence mapping	Consider the future as a series of events taking account of probability of event's occurrence	Narrative is understandable to audience	Events difficult to classify and organize
5	Backcasting	- horizon mission methodology - Impact of Future Technologies - future mapping	Work back from a future state to identify how to get there	Creative and reduces tendency to extrapolate from past/present	Future state may seem fantastical and reduce participation
6	Dimensions of uncertainty	- morphological analysis - field anomaly relaxation - GBN - MORPHOL - OS/SE	Identifies specific sources of uncertainty and uses those as the basis for alternative futures	Useful where uncertainties are known	May not recognise developments where uncertainties are unknown
7	Cross-impact analysis	- SMIC-PROB-EXPERT - IFS	Takes account of probability of one event is contingent on the occurrence of other events	Calculates final probability using robust mathematical procedures	Highly complex and difficult to validate assumptions of all event probabilities
8	Modelling	- trend impact analysis - sensitivity analysis - dynamic scenarios	Similar to baseline/ expected but creates additional scenarios by varying inputs	Good quantitative representation of continuous variables describing a future	Difficult to validate models without complete historical data

Many energy scenarios have been produced by different actors with an interest in the future GB electricity system using different techniques. Scenarios, such as those produced by UKERC using the UK MARKAL energy systems model, have used the modelling technique whereas transition pathway scenarios, such as “Transition Pathways to a Low Carbon Economy” [13], have used event sequences and backcasting techniques.

The scenarios described in this chapter, use the baseline/expected technique to project existing technology, cost and policy trends to future periods.

3.3 Review of optimization techniques

There are three main techniques used for optimization, identified in [14]:-

- Mathematical
- Artificial Intelligence
- Hybrid

3.3.1 Mathematical (algorithmic) models

In optimization of an energy system the objective function is defined to minimize or maximize an objective by varying resource inputs (design variables) subject to defined constraints. This approach is mathematically rigorous and can utilise a wide range of programming technologies such as linear programming (LP), interior point method (IP), quadratic programming (QP), nonlinear programming (NLP), decomposition, integer and mixed integer programming, and dynamic programming (DP).

3.3.2 Artificial Intelligence (AI) Techniques (heuristic and stochastic)

These techniques are used where problems require inputs involving judgement, experience, characterization and human knowledge to solve. There are a number of AI techniques including expert system (ES), artificial neural networks (ANN), fuzzy logic, evolutionary computation (EC), genetic algorithm (GA), simulated annealing (SA), ant colony search (ACS) and tabu search (TS).

3.3.3 Hybrid Techniques

Hybrid techniques are used to combine the strengths of the different techniques and overcome some of the weaknesses.

3.3.4 Excel Solver

There are many proprietary optimizer tools including Excel Solver, MATLAB, Fico Xpress etc. Familiarity with the Excel spreadsheet tool resulted in Solver being used as the optimizer platform.

Solver, developed by Frontline Systems Inc as an “Add-in” function to MS Office Excel spreadsheet package, is a general purpose optimization modelling system which combines the functions of a graphical user interface (GUI), an algebraic modelling language e.g. GAMS or AMPL, and optimizers for linear, non-linear and integer programs. It starts with an ordinary Excel spreadsheet model whose formula language functions as the algebraic language used to define the optimizer model. It uses the generalized reduced gradient method (GRG) as a default, and the simplex method for defined linear problems.

The purpose of the tool is to find an optimal solution, i.e. values for the identified decision variables, which satisfies the stated constraints and minimizes or maximizes the objective function, using the generalized reduced gradient (GRG) method.
Solutions can be feasible, good or optimal, depending on the mathematical relationships between the variables, objective function and constraints.

The spreadsheet model created for this study is a non-linear, smooth, non-convex model, which allows the optimizer to calculate a locally optimal solution, i.e. with no other feasible solution in the vicinity with a more optimal objective function value. The solution can be improved by starting the model at a variety of different points i.e. with different decision variable values, to explore a wider range of peaks and troughs (convex and concave) in the model landscape.

The model inputs are as shown in Table 3.2.

Table 3.2 Description of inputs to generation mix optimization model

Optimizer Input	**Description**
Objective function	- Minimize total system cost (£m/yr)
Decision variables	- Installed capacities (GW) - Plant load factors (%)
Constraints	- Min and max capacities for individual technologies (GW) - Maximum plant load factors (%) - Total capacity (GW) - Total output (TWh/yr) - Maximum average emissions (gCO_2/kWh) - Percentage of renewable and low carbon generation of total annual output - Maximum percentage of individual technologies to total annual output - Maximum percentage of non-dispatchable generation to total annual output - Minimum Shannon-Weiner index of diversity

3.4 Basis of Optimization model

The optimization model used in this study is subject to input variables including future energy policy targets, capacity for different generating technologies, and costs. These input variables are generated using the baseline/expected technique described in Table 3.1 Categories of techniques used in scenario development (adapted from [12]).

The outputs from the model are optimized generating technology mixes for 2020, 2030 and 2050. The objective function, to minimize annual cost, is subject to technology capacity and plant load factor decision variables, and emission, capacity and diversity constraints.

3.4.1 Technology capacity

Technology capacity is the amount of generating capacity for each generating technology which may be available in the future. Factors which determine the amount of capacity include physical constraints, such as available space to site the plants, sources of fuel, time to construct new infrastructure, and the pace of development of new technologies. They also include policy constraints which seek to encourage or limit the development of individual generating technologies, despite a stated desire of Government to be technology neutral in its energy policy.

Other factors affecting technology capacity include the ability of each generating technology to produce electricity over the lifetime of the plant, described by its plant load factor (PLF).

The physical constraints for fossil fuel technologies, nuclear, and other low carbon technologies, are set out below.

3.4.1.1 Fossil fuel generating technologies

The main fossil fuel generating technologies (coal and natural gas), which make up 65% of the 2012 UK generating capacity [1], occupy a small amount of space relative to the amount of electricity they produce. A typical 2,000MW CCGT plant will occupy a site of 90ha [15] which, with a 50% PLF gives a notional power per unit area of 1,111W/m^2 (2,000MW x 50%PLF/90ha = 1,111W/m^2). Spatial constraints on these plants include planning regulations and visual impact, access to primary fuel supply, access to the transmission network, and proximity to load centres.

The development of carbon capture and storage (CCS) technologies, for use with fossil fuel plants, require space to store the captured CO_2. Potential sites for storage include depleted oil and gas reservoirs on the UKCS, such as off the Humberside coast being investigated by National Grid and estimated to have the capacity to store approx. 200 million tonnes of CO_2 (16).

The decline in natural gas extraction from the UK Continental Shelf (UKCS), from a peak of 114,663 million cubic metres in 2000 [17] to 41,089 million cubic metres in 2012 [1], is projected to continue, albeit at a slower rate [18]. The almost complete closure of the GB coal fields (16.3 million tonnes produced in 2012 [1] compared with a peak of 287 million tonnes in 1913 [19] and 64.2 million tonnes consumption in 2012 [1]) requires the importation of gas and coal from overseas.

There is currently a plentiful supply of gas and coal on the global market [20] which is projected to continue into the medium term [21] aided by new extraction techniques, such as hydraulic fracturing (“fracking”). Despite this, future supplies cannot be guaranteed and may be subject to geopolitical developments which could interrupt supplies.

CCS is still in the early stages of development and has not yet been commercially proven at large scale (the largest demonstration of CCS as at August 2013 was the 5MWe Ferrybridge project launched in November 2011) [22]. The introduction of CCS across fossil fuel plants is uncertain and may not be available for practical use until the early 2020’s with capacity growth constraints limiting deployment to “up to” 15GW by 2030 [23]. This can be viewed in the context of 62.3GW of coal and gas capacity (TEC) in 2012 [1].

Fossil fuel plants can be built relatively quickly (typically 30 months for a CCGT plant using medium assumptions [24]) and use established technologies.

3.4.1.2 Nuclear generating technologies

Nuclear plants, which make up 10% of the 2012 generating capacity and 18% of electricity produced [1], have a power unit per unit area of approx 1,000W/m^2 [25]. Other spatial constraints are similar to coal and gas plants though access to fuel (mainly Uranium 235) is less critical (in terms of distribution infrastructure) due to the relatively small amounts required. A further physical constraint is the management of waste which needs to be stored and disposed of in geological containment for over 1,000 years.

Geological stability is of greater importance to the siting of nuclear plants than traditional fossil fuel plants, and the time to build a new plant is significantly longer. A new nuclear plant can take between 10 and 15 years to build from inception [24] and cost and time overruns are not uncommon.

3.4.1.3 Other low carbon generating technologies

Other low carbon technologies such as wind and solar plants have far lower power per unit area than nuclear or gas and coal, with on shore wind farms having outputs of between 2.0 – 3.4W/m^2 depending on location [26]. Space between individual wind turbines can, however, be used for other purposes, such as agriculture and recreational pursuits, with the turbine footprints typically taking up only 1% of the total area.

The UK land mass has the potential for 110GW of wind capacity, not including land used for other means or in areas of ecological sensitivity [27]. Of this, 28GW is assessed as being the maximum practical resource due to clustering and proximity constraints. This compares with 16GW if compared to the same density as Denmark. Public opposition to large scale wind farms (e.g. [28]) acts as a constraint to development despite studies indicating support for greater amounts of renewable capacity [29].

Solar power has the advantage that small scale installations can be sited on existing structures, such as the roofs of existing buildings, and, therefore, not require additional space. Large scale solar PV installations may be sited in open areas which would have a greater impact.

Hydro power can be separated into pumped storage and reservoirs, tidal and wave.

UK pumped storage capacity (TEC) in 2012 is 2.7GW [1]. Due to the special geographic features required for pumped storage and reservoirs i.e. large collection area, contained bowl and sufficient elevation to generate head, further capacity is limited. Some sources estimate a further 850 -1550MW of hydro potential remains in the UK [30].

Great Britain benefits from a large coastline (11,073 miles, though this can vary depending on scale of measurement [31]), and some excellent tidal and wave resources. Resource potential for wave is 27GW, tidal stream 32GW, tidal barrage 45GW, and tidal lagoons 14GW [32]. Technologies to exploit wave energy are being developed and the UK’s resource has the potential to generate 69TWhpa [32].

An advantage of offshore resources, such as wave and off-shore wind, is that there is limited visual impact on land-based populations. Disadvantages, however, include higher costs, negative impacts on shipping and fishing, more hostile environment affecting maintenance and generating plant life, and the requirement to deliver electricity from off-shore locations to land with potential damage to the marine environment.

3.4.2 Costs

Projecting costs for the UK electricity system is highly speculative due to the large number of variables involved and the range of feasible values for each variable. These variables include:- fuel cost differentials; cost of carbon and whether based on “stack” emissions or life cycle assessment (LCA) emissions; plant load factors; degree of maturity of technology and whether costed on a “first of a kind” (FOAK) or “nth of a kind” (NOAK) basis; market conditions; legislation and regulation (costs to operate); levies and taxes; exchange rate fluctuations; cost and availability of finance; perceptions of risk; global competition for resources and funding; extent and impact of variability; grid charges and generator locations in relation to load; and demand levels and characteristics.

A method to allow the comparison of costs over different technologies is levelized cost of electricity (LCOE). This has been defined by the OECD and IEA as the “ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalents” [33]. Other definitions include that of consultant, Mott MacDonald, who defines LCOE as “the discounted lifetime cost of ownership of using a generation asset converted into an equivalent unit cost of generation in £/MWh or p/kWh. This is sometimes called a life cycle cost, which emphasises the cradle to grave aspect of the definition” [34]. This definition has been adopted by DECC [35].

The LCOE of a generating technology, described in [36], is calculated using the following equation {2}.

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \qquad \{2\}$$

I_t = Investment expenditure in year t
M_t = O&M expenditure in year t
F_t = Fuel expenditure in year t
E_t = Electricity generated in year t
r = Discount rate
n = expected life of investment

One way of reducing the cost sensitivity from plant load factor assumptions is to decouple the capital costs involved in engineering, procurement and construction (EPC), and fixed costs, from assumed levels of output. These costs are, instead, allocated across the operating life of the plant. This method is used in the optimization model cost calculations in this study.

3.5 UK electricity supply optimization

The objective of the study is to produce an optimized generating technology mix for the UK for 2020, 2030 and 2050. Costs are limited to generation costs and connection to the transmission grid. Other costs, such as for land and transmission and distribution, are not included.

3.5.1 Methodology

An Excel spreadsheet model was developed which incorporates policy targets, generating technologies, practical capacity limitations and costs, and optimization software is engaged to calculate different generation mixes.

The model includes sections for policy targets, technologies, capacities, costs, emissions and security of supply, and the Solver function within Excel is set to minimize the total system cost by varying the amount of capacity and load factors per technology, subject to constraints.

3.5.1.1 Targets

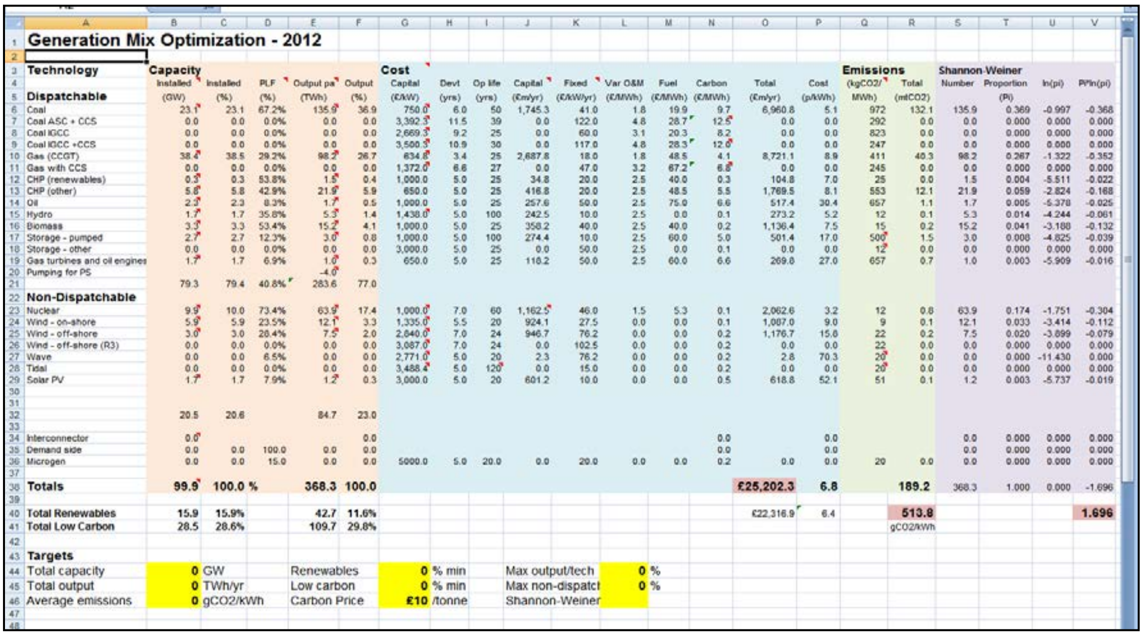
The targets contained within the spreadsheet are as shown in Table 3.3.

Table 3.3 Targets used in generation mix optimization model

	2012 (reference year)	**2020**	**2030**	**2050**
Total capacity (GW)	99.9	115	155	200
Total output (TWhpa)	368.3	430	560	830
Average emissions (gCO_2/kWh)	513.8	250	100	50
Renewables output (minimum) (%)	11.6	30	0	0
Low carbon output (minimum) (%)	29.8	40	0	0
Carbon price (£/tonne)	10	18	70	150
Max output/technology (%)	36.9 (coal)	50	50	50
Max non-dispatchable output (%)	22.7	50	60	72
Shannon-Weiner Index	1.696	1.500	1.500	1.500

3.5.1.2 Spreadsheet model

The initial stage of the exercise was to create a spreadsheet model establishing a link between the different elements of supply. A screenshot of the spreadsheet is shown in Figure 3.4.



Generation Mix Optimization - 2012

Technology	**Capacity**					**Cost**										**Emissions**		**Shannon-Weiner**			
	Installed	Installed	PLF	Output pa	Output	Capital	Devt	Op life	Capital	Fixed	Var O&M	Fuel	Carbon	Total	Cost	(kgCO2/	Total	Number	Proportion	ln(pi)	Pi*ln(pi)
Dispatchable	(GW)	(%)	(%)	(TWh)	(%)	(£/kW)	(yrs)	(yrs)	(£m/yr)	(£/kW/yr)	(£/MWh)	(£/MWh)	(£/MWh)	(£m/yr)	(p/kWh)	MWh)	(mtCO2)		(Pi)		
Coal	23.1	23.1	67.2%	135.9	36.9	750.0	6.0	50	1,745.3	41.0	1.8	19.9	9.7	6,960.8	5.1	972	132.1	135.9	0.369	-0.997	-0.368
Coal ASC + CCS	0.0	0.0	0.0%	0.0	0.0	3,392.3	11.5	39	0.0	122.0	4.8	28.7	12.5	0.0	0.0	292	0.0	0.0	0.000	0.000	0.000
Coal IGCC	0.0	0.0	0.0%	0.0	0.0	2,669.3	9.2	25	0.0	60.0	3.1	20.3	8.2	0.0	0.0	823	0.0	0.0	0.000	0.000	0.000
Coal IGCC +CCS	0.0	0.0	0.0%	0.0	0.0	3,500.3	10.9	30	0.0	117.0	4.8	28.3	12.0	0.0	0.0	247	0.0	0.0	0.000	0.000	0.000
Gas (CCGT)	38.4	38.5	29.2%	98.2	26.7	634.8	3.4	25	2,687.8	18.0	1.8	48.5	4.1	8,721.1	8.9	411	40.3	98.2	0.267	-1.322	-0.352
Gas with CCS	0.0	0.0	0.0%	0.0	0.0	1,372.0	6.6	27	0.0	47.0	3.2	67.2	6.8	0.0	0.0	245	0.0	0.0	0.000	0.000	0.000
CHP (renewables)	0.3	0.3	53.8%	1.5	0.4	1,000.0	5.0	25	34.8	20.0	2.5	40.0	0.3	104.8	7.0	25	0.0	1.5	0.004	-5.511	-0.022
CHP (other)	5.8	5.8	42.9%	21.9	5.9	650.0	5.0	25	416.8	20.0	2.5	48.5	5.5	1,769.5	8.1	553	12.1	21.9	0.059	-2.824	-0.168
Oil	2.3	2.3	8.3%	1.7	0.5	1,000.0	5.0	25	257.6	50.0	2.5	75.0	6.6	517.4	30.4	657	1.1	1.7	0.005	-5.378	-0.025
Hydro	1.7	1.7	35.8%	5.3	1.4	1,438.0	5.0	100	242.5	10.0	2.5	0.0	0.1	273.2	5.2	12	0.1	5.3	0.014	-4.244	-0.061
Biomass	3.3	3.3	53.4%	15.2	4.1	1,000.0	5.0	25	358.2	40.0	2.5	40.0	0.2	1,136.4	7.5	15	0.2	15.2	0.041	-3.188	-0.132
Storage - pumped	2.7	2.7	12.3%	3.0	0.8	1,000.0	5.0	100	274.4	10.0	2.5	60.0	5.0	501.4	17.0	500	1.5	3.0	0.008	-4.825	-0.039
Storage - other	0.0	0.0	0.0%	0.0	0.0	3,000.0	5.0	25	0.0	50.0	2.5	0.0	0.1	0.0	0.0	12	0.0	0.0	0.000	0.000	0.000
Gas turbines and oil engines	1.7	1.7	6.9%	1.0	0.3	650.0	5.0	25	118.2	50.0	2.5	60.0	6.6	269.8	27.0	657	0.7	1.0	0.003	-5.909	-0.016
Pumping for PS				-4.0																	
	79.3	79.4	40.8%	283.6	77.0																
Non-Dispatchable																					
Nuclear	9.9	10.0	73.4%	63.9	17.4	1,000.0	7.0	60	1,162.5	46.0	1.5	5.3	0.1	2,062.6	3.2	12	0.8	63.9	0.174	-1.751	-0.304
Wind - on-shore	5.9	5.9	23.5%	12.1	3.3	1,335.0	5.5	20	924.1	27.5	0.0	0.0	0.1	1,007.0	9.0	9	0.1	12.1	0.033	-3.414	-0.112
Wind - off-shore	3.0	3.0	28.4%	7.5	2.0	2,840.0	7.0	24	946.7	76.2	0.0	0.0	0.2	1,176.7	15.8	22	0.2	7.5	0.020	-3.899	-0.079
Wind - off-shore (R3)	0.0	0.0	0.0%	0.0	0.0	3,087.0	7.0	24	0.0	102.5	0.0	0.0	0.2	0.0	0.0	22	0.0	0.0	0.000	0.000	0.000
Wave	0.0	0.0	6.5%	0.0	0.0	2,771.0	5.0	20	2.3	76.2	0.0	0.0	0.2	2.8	70.3	20	0.0	0.0	0.000	-11.430	0.000
Tidal	0.0	0.0	0.0%	0.0	0.0	3,488.4	5.0	120	0.0	15.0	0.0	0.0	0.2	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
Solar PV	1.7	1.7	7.9%	1.2	0.3	3,000.0	5.0	20	601.2	10.0	0.0	0.0	0.5	618.8	52.1	51	0.1	1.2	0.003	-5.737	-0.019
	20.5	20.6		84.7	23.0																
Interconnector	0.0				0.0								0.0		0.0			0.0	0.000	0.000	0.000
Demand side	0.0	0.0	100.0	0.0	0.0								0.0		0.0			0.0	0.000	0.000	0.000
Microgen	0.0	0.0	15.0	0.0	0.0	5000.0	5.0	20.0	0.0	20.0	0.0	0.0	0.2	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
Totals	**99.9**	**100.0**	**%**	**368.3**	**100.0**									**£25,202.3**	**6.8**		**189.2**	368.3	1.000	0.000	-1.696
Total Renewables	**15.9**	**15.9%**		**42.7**	**11.6%**									£22,316.9	6.4		**513.8**				**1.696**
Total Low Carbon	**28.5**	**28.6%**		**109.7**	**29.8%**												gCO2/kWh				
Targets																					
Total capacity	**0**	GW		Renewables		**0**	% min		Max output/tech		**0**	%									
Total output	**0**	TWh/yr		Low carbon		**0**	% min		Max non-dispatcl		**0**	%									
Average emissions	**0**	gCO2/kWh		Carbon Price		**£10**	/tonne		Shannon-Weiner												

Figure 3.4: Generation mix optimization screenshot

3.5.1.3 Technologies

Technologies are categorised under two main headings of dispatchable and non-dispatchable. The technologies were selected from current technologies described in the Digest of United Kingdom Energy Statistics (DUKES) [1] and significant future technologies where cost data were available from the DECC Electricity Generating Costs 2013 report [35], and represent the current expectation of the main generation technologies which will be available within the timeframe of the study. The dispatchable technologies are as follows:-

- Coal ASC (advanced supercritical coal)
- Coal ASC + CCS (carbon capture and storage)
- Coal IGCC (integrated gasification combined cycle)
- Coal IGCC +CCS
- Gas (CCGT) (combined cycle gas turbine)
- Gas + CCS
- CHP (renewable) (combined heat and power)
- CHP (other)
- Oil
- Hydro
- Biomass
- Storage – pumped
- Storage – other
- Gas turbines and oil

- Pumping for pumped storage

The non-dispatchable technologies are as follows:-

- Nuclear
- Wind – on-shore
- Wind – off-shore
- Wind – off-shore (R3) (round 3)
- Wave
- Tidal
- Solar PV (photovoltaic)

3.5.1.4 Capacities

The capacity section is split into five sections:-

- Installed (GW)
- Installed (%)
- Plant Load Factor (%)
- Output pa (TWh)
- Output (%)

Installed capacity is the total capacity of each technology within the UK and is expressed in absolute terms i.e. GW, and as a percentage of the total system capacity. Plant load factors refer to the availability of generation plant to produce electricity.

The total annual output is expressed in absolute terms (TWh) and as a percentage.

It is recognised that the capacity model is highly simplified and does not take into account diurnal, weekly or seasonal variations in demand profiles relating to system capacity constraints. Notwithstanding this, the minimum constraints on total output, linked with the other constraints on emissions, plant load factors etc, lead to an overall system installed capacity which recognises variation in demand.

Capacity constraints for each technology were calculated on the basis of existing capacity at each prior time point less plant retirals plus new capacity installed during the period. In addition, minimum capacities have been introduced to avoid unrealistic reductions in capacity where plant already exists e.g. hydro, pumped storage and off-shore wind.

Selected capacity constraints were also introduced from other sources including DECC [37], Arup [38], The Crown Estates [32] and UKERC [23], as shown in Table 3.4:-

Table 3.4 Capacity constraints (max/min) (GW)

Technology	**2012 (reference year)**[1]	**2020**	**2030**	**2050**
Coal	23.1	no/0.0	no/0.0	no/0.0
Gas	38.4	35.1/16.2	no/0.0	no/0.0
CHP (renewables)	0.3	no/0.0	no/0.0	no/0.0
CHP (other)	5.8	no/0.0	no/0.0	no/0.0
Oil	2.3	no/0.0	no/0.0	no/0.0
Hydro	1.7	2.0/1.7[1]	2.0/1.7[1]	2.0/1.7[1]
Biomass	3.3	no/0.0	no/0.0	no/0.0
Pumped Storage	2.7	4.0/2.7[1]	4.0/2.7[1]	4.0/2.7[1]
Gas Turbines & Oil Engines	1.7	no/0.0	no/0.0	no/0.0
Nuclear	9.9	9.6/0.0	14.0/0.0	38.4/0.0
Wind – onshore	5.9	13.0[2]/0.0	24.0/0.0	28.0[2]/0.0
Wind – offshore	3.0	16.0[2]/0.0	16.0[2]/0.0	16.0/0.0
Wind – offshore R3	0.0	2.0[2]/0.0	24.0[2]/0.0	64.0/0.0
Wave	0.0	0.3/0.0	2.5[3]/0.0	27.0[4]/0.0
Tidal	0.0	1.3/0.0	8.6/0.0	24.9/0.0
Solar PV	1.7	13.5[2]/0.0	19.0[3]/0.0	40.0/0.0
CCS	0.0	2.5/0.0	15.0[5]/0.0	50.0/0.0
CHP	6.1	15.0/0.0	no/0.0	no/0.0
Renewable/biomass (CHP & biomass)	3.6	20.0/0.0	20.0/0.0	20.0/0.0

[1] DUKES 2013 [1]

[2] Renewables Roadmap 2012 [37]

[3] Arup 2011 high scenario [38]

[4] The Crown Estate [32]

[5] UKERC Realising the potential [23]

Plant load factors are sourced from DUKES [1], Parsons Brinckerhoff (availability factors) [24], and DECC [39], as shown in Table 3.5:-

Table 3.5 Plant Load Factors (%)

Technology	**2012 (reference year)**	**2020**	**2030**	**2050**
Coal	67.2	91.9	80.0	80.0
Gas	29.2	93.7	80.0	80.0
CHP (renewables)	53.8	60.0	60.0	60.0
CHP (other)	42.9	80.0	80.0	80.0
Oil	8.3	50.0	50.0	50.0
Hydro	35.8	36.5	36.5	36.5
Biomass	53.4	60.0	60.0	60.0
Pumped Storage	12.3	15.0	15.0	15.0
Gas Turbines & Oil Engines	6.9	60.0	60.0	60.0
Nuclear	73.4	80.0	90.0	90.0
Wind – onshore	23.5	27.7	30.0	30.0
Wind – offshore	28.4	32.5	35.0	35.0
Wind – offshore R3	N/A	35.0	40.0	40.0
Wave	6.5	36.5	36.5	36.5
Tidal	N/A	18.8	18.8	18.8
Solar PV	7.9	10.4	17.0	17.0

3.5.1.5 Costs

As noted above, the projection of generating costs is highly speculative given the high levels of uncertainty over the many influencing factors. The primary source of cost data is the DECC Electricity Generating Costs 2013 report [35] and supporting sources. Notwithstanding the uncertainty regarding future costs, the spreadsheet analysis and optimization give a comparison between the relative costs of each technology as they are currently understood, and provide an indication of the order of merit under these conditions.

The cost section is split into ten sections:-

- Capital (£/kW)
- Development (years)
- Operating life (years)

- Capital (£m/yr)
- Fixed (£/kW/yr)
- Variable O&M (£MWh)
- Fuel (£/MWh)
- Carbon (£/MWh)
- Total (£m/yr)
- Cost (p/kWh)

Capital costs, expressed in terms of £/kW capacity installed, have been separated from the other elements of levelized costs in order to decouple the initial costs involved in creating the generating plant from an assumed lifetime output. Capital costs have instead been expressed as an equivalent annual cost (EAC) by utilising the following equation {3}:-

$$\mathrm{EAC_t} = \frac{\left((\mathrm{CC_t} \times \mathrm{IC_t}) \times \mathrm{R}\right)}{(1-(1+\mathrm{R})^{-\mathrm{OL}})} \qquad \{3\}$$

where:-

CC_t	capital cost per technology (£/kW)
EAC_t	equivalent annual cost per technology (£m/yr)
IC_t	installed capacity per technology (GW)
OL	operating life (years)
R	discount rate

This gives a more realistic assessment of costs than using an assumed level of output over a planned lifetime incorporated within a levelized cost figure i.e. it removes the uncertainty of plant load factors on the spreading of capital costs through the operational lifetime of the plant. Capital costs have been derived from a combination of the DECC Electricity Generating Costs 2013 report [35], DECC 2050 analysis and estimated amounts. They vary between first of a kind (FOAK) and nth of a kind (NOAK) cost depending on the assumed level of development and maturity, as shown in Table 3.6.

Table 3.6 Technology maturity and cost categories

Technology	**2020**	**2030**	**2050**
Coal ASC	High FOAK	Low FOAK	Low NOAK
Coal ASC + CCS	High FOAK	Low FOAK	Low NOAK
Coal IGCC	High FOAK	Low FOAK	Low NOAK
Coal IGCC + CCS	High FOAK	Low FOAK	Low NOAK
Gas CCGT	Low NOAK	Low NOAK	Low NOAK
Gas CCGT + CCS	High FOAK	Low FOAK	Low NOAK
CHP (renewables)	Low NOAK	Low NOAK	Low NOAK
CHP (other)	Low NOAK	Low NOAK	Low NOAK
Oil	1,000*	1,000*	1,000*
Hydro	DECC 2050 low 2020	DECC 2050 low 2020	DECC 2050 low 2020
Biomass	Low NOAK	Low NOAK	Low NOAK
Storage – pumped	1,000*	1,000*	1,000*
Storage – other	3,000*	3,000*	3,000*
Gas turbines & oil engines	650*	650*	650*
Nuclear	Low NOAK	Med FOAK	Med NOAK
Wind – on-shore	Low NOAK	Low NOAK	Low NOAK
Wind – off-shore	Med NOAK	Low NOAK	Low NOAK
Wind off-shore (R3)	Med FOAK	Med NOAK	Low NOAK
Wave	DECC 2050 high 2020	DECC 2050 med 2020	DECC 2050 central 2020
Tidal	£30bn for 8.6GW Severn Barrage	£30bn for 8.6GW Severn Barrage	£30bn for 8.6GW Severn Barrage
Solar PV	Medium	Low	Low

* £/kW

Cost allocations are based on a mixture of new and existing capacity current at the time indicated on each spreadsheet e.g. in 2030 there could be five new nuclear plants (8,000MW) and three existing sites/plants (6,048MW including deferred retirals from 2023 and 2019), giving a mix of low NOAK (existing) and high – med FOAK (new).

Carbon costs are based on the target carbon floor price within the Electricity Market Reform White Paper, and as detailed in the March 2012 UK Budget, as follows:-

- 2012 - £10/tCO_2 (est)
- 2014 - £16/tCO_2
- 2020 - £30/tCO_2*
- 2030 - £70/tCO_2
- 2050 - £150/tCO_2 (est)

* The March 2014 UK Budget capped the carbon price support level at £18/tCO_2 to 2019/20 [40] and this has been used in the spreadsheet model.

Total costs {4} are built up using capital costs (£/kW), expressed as an equivalent annual cost (£m/yr) {2}, fixed operating and maintenance costs (£/kW/yr), variable operating and maintenance costs, fuel costs and carbon costs (£/MWh), using a number of different assumptions including plant operating life, discount rate, emissions factors, decommissioning costs, cost of carbon and the stage of technological development.

$$\mathrm{TC_t} = \mathrm{EAC_t} + (\mathrm{FC_t} \times \mathrm{IC_t}) + \left((\mathrm{VC_t} + \mathrm{FC_t} + \mathrm{EC_t}) \times \mathrm{O_t}\right) \quad \{4\}$$

where:

EC_t emissions cost per technology (£/MWh)
FC_t fixed costs per technology (£/MWh)
O_t annual output per technology (TWh)
TC_t total cost per technology (£m/yr)
VC_t variable operating and maintenance costs (£/MWh)

Costs per kWh (p/kWh) are calculated as {5}:-

$$\mathrm{UC_t} = \frac{\mathrm{TC_t}}{(\mathrm{O_t} \times 10)} \quad \{5\}$$

where:-

UC_t unit cost per technology (p/kWh)

The method used for calculating total costs has drawn on data from the DECC Electricity Generating Costs 2013 [35] and supporting reports, though instead of using levelized costs across all elements of cost, annualised costs have been calculated to address the capital costs involved in engineering, procurement and construction (EPC), and emissions/carbon costs have been more closely linked to emissions factors and the cost of carbon. This was done to improve the sensitivity of the model to different technology plant load factors and to identify the impact different levels of carbon pricing have on the overall cost of generation.

3.5.1.6 Emissions

The European Union Emissions Trading System (EU ETS) is an Europe wide cap and trade scheme which places a price on CO_2 emissions directly linked to the electricity generating activities of the plant (“stack” emissions). This, however, does not address the wider impact of emissions incurred at other stages of the process such as extraction and processing of fuels, construction of generating plant and equipment, carbon sequestration activities, and end of life impacts, nor does it address the emissions of other greenhouse gases (GHG) including nitrous oxide (NO_x) and methane (CH_4). These can be collectively assessed through a process of life cycle assessment (LCA) as shown in Figure 3.5.

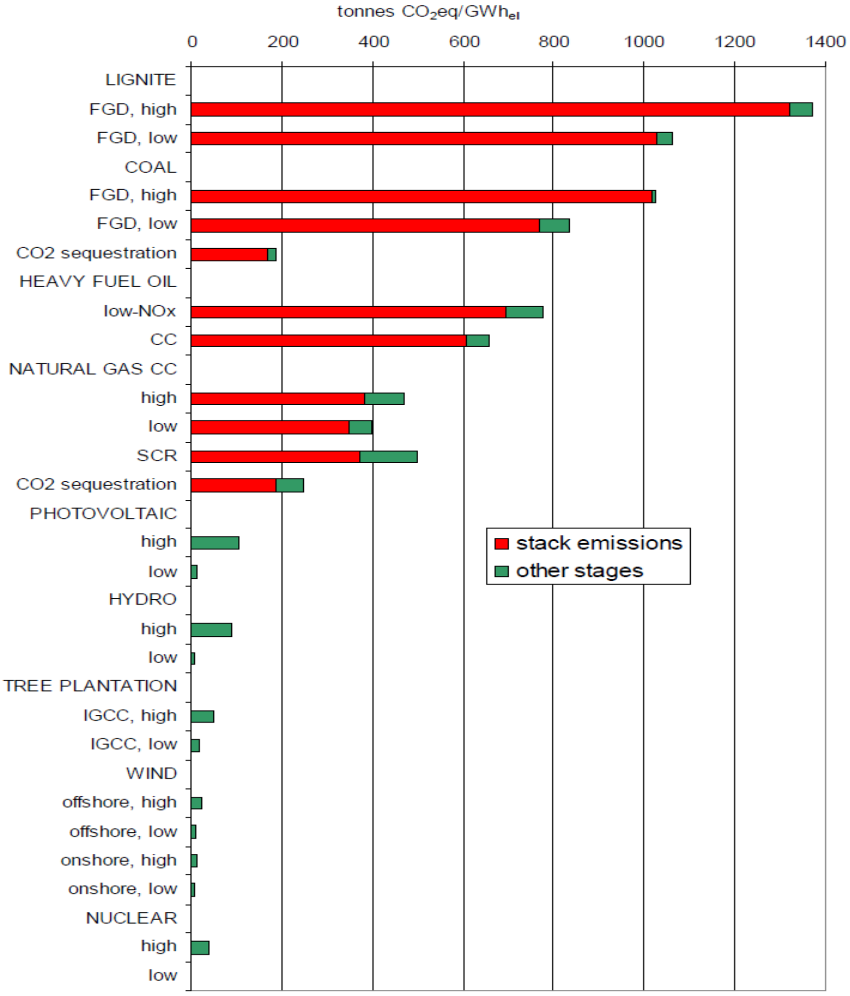


Figure 3.5 LCA emissions from various technologies [41]

The emissions used in the optimization model are as shown in Table 3.7.

Table 3.7 Emissions used in spreadsheet (gCO_2/kWh)

Technology	**LCA emissions gCO_2/kWh**
Coal	972
Coal ASC + CCS	292
Coal IGCC	823
Coal IGCC + CCS	247
Gas (CCGT)	411
Gas + CCS	245
CHP (renewables)	25
CHP (other)	553
Oil	657
Hydro	12
Biomass	15
Pumped Storage	500
Gas Turbines & Oil Engines	657
Nuclear	12
Wind – onshore	9
Wind – offshore	22
Wind – offshore R3	22
Wave	20
Tidal	20
Solar PV	51

The UK Climate Change Act, 2008, sets out a target of 34% reduction in all GHG emissions by 2030 and 80% reduction by 2050 (compared with 1990 levels) and it is, therefore, conceivable that carbon pricing will extend to other industries and processes, thereby increasing costs within the power generating sector. The emissions factors used in the model are, therefore, based on LCA emissions involved in the generation of each technology, expressed in gCO_{2equ}/kWh.

Total emissions ($mtCO_{2equ}$) for each technology are calculated by:-

$$\mathrm{TE_t = O_t \; x \; EF_t} \qquad \{6\}$$

and the system emission factor (EF_S) expressed in gCO_{2equ}/kWh by:-

$$EF_S = \frac{TE_S}{O_S} \times 1000 \qquad \{7\}$$

The system emission factor is then set against the targets set for average emissions by the Committee for Climate Change in their Fourth Carbon Budget [42] and partially supported by the UK Government i.e. 300gCO_2/kWh by 2020 and 50 - 100gCO_2/kWh by 2030, compared with between 443 – 559gCO_2/kWh in 2012 [43]. These targets are based on projections which change depending on prevailing market conditions. The review of the Fourth Carbon Budget in December 2013 [44] amended the projection for 2020 to 211gCO_2/kWh.

3.5.1.7 Security of Supply

Security of supply has been defined by Grubb [45] as “a system’s ability to provide a flow of energy to meet demand in an economy, in a manner and price that does not disrupt the course of the economy”, and includes price stability and the quality and consistency of supply.

The vulnerability of an electricity system to risk, uncertainty and ignorance (“incertitude” as described by Stirling 1994 [46]) can be reduced through analysing system diversity using principles based on biodiversity studies. Two main types of diversity indices are used i.e. ecological and economic [47] as shown in Figure 3.6.

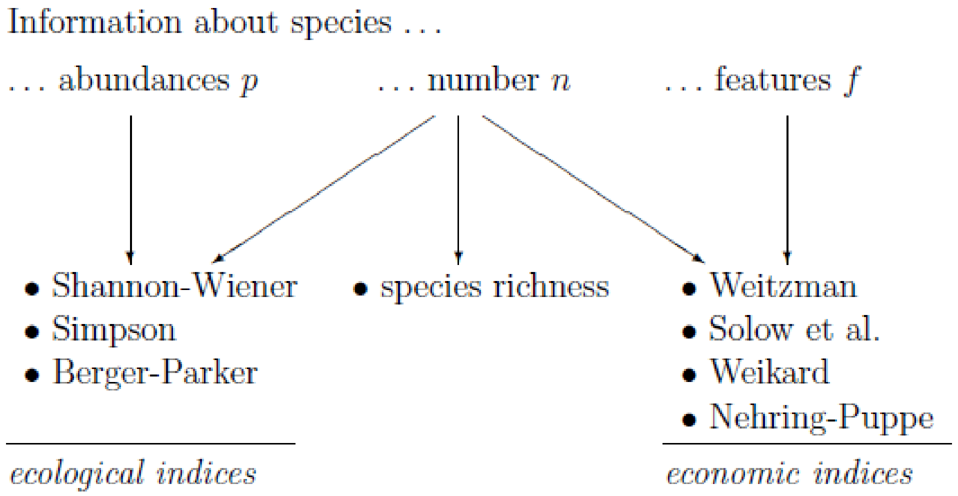


Figure 3.6 Biodiversity indices and species and ecosystems composition [47]

Both indices draw on the concept of species richness i.e. the total number of different species within the system. In the context of this study species richness refers to the number of different generation technologies present within the system. The main difference between the two categories is that the ecological indices recognise relative abundances of species within the system whereas the economic indices pay more attention to the characteristic features, including the (dis)similarity between the species.

The ecological indices are based on the concept of whole system stability and resilience, whereas the economic indices are based on the concept of individual choice and individual utility maximization.

The principle of product diversity, where choice is supported by the ability to increase abundance by production, is contained within the economic indices, whereas the ecological indices are based on the principle that biological species abundances are natural processes and not easily produced.

Given the nature of electricity generation plant, the timescales required for development and construction, the long duration of plant life, the high capital costs involved and the necessity for overall system stability, a diversity index, based on the principles of abundance and richness, is used in this study.

The methodology used to measure the degree of supply security in this study is the Shannon-Weiner index, which is an ecological index measuring species richness, i.e. the number of different generating technologies, and species abundance, i.e. the proportion of an individual technology's output within the overall system output:-

$$\mathrm{H_T} = \sum_{\mathrm{i}=1}^{\mathrm{S}} \mathrm{p_i} \ln \mathrm{p_i} \qquad \{8\}$$

Where:-

H_T	index of species diversity
ln	natural log
p_i	proportion of total sample belonging to the i^{th} species
S	species richness (total number of species present)

3.5.2 Results from optimization model

The results of the optimization (Table 3.8) show a progression from mainly fossil fuel driven, dispatchable power stations, to a more even balance between dispatchable stations (CCGT, IGCC with CCS, renewable CHP and biomass), base-load (nuclear) and intermittent renewable (on and off-shore wind and solar PV). Nuclear output falls from 17.4% of total output in 2012 to 15.6% of total output in 2020 due to plant retirals. New capacity is available by 2030, offsetting further retirals, allowing an increase in output to 19.8%.

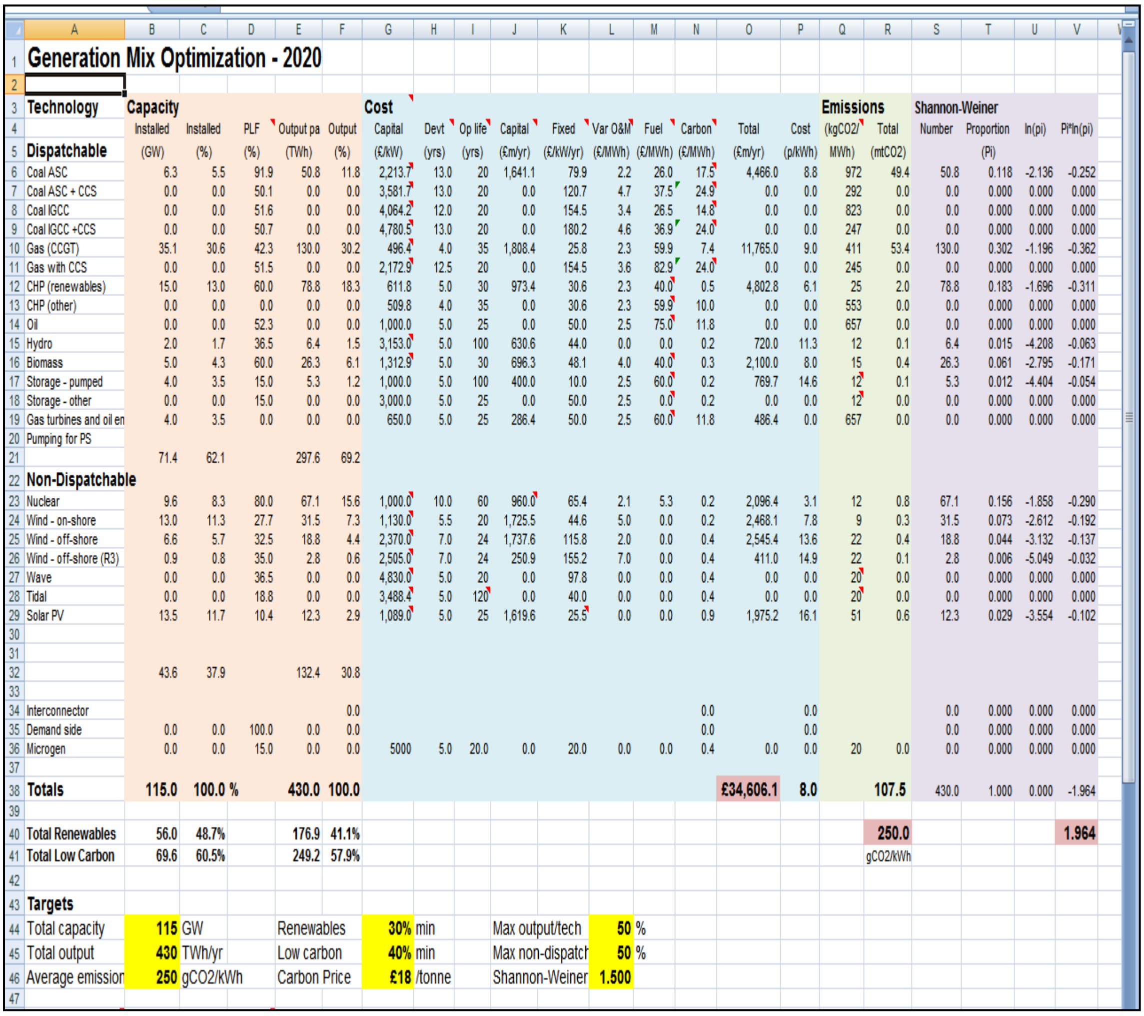
Table 3.8 Generation mix optimization – summary results

	2012	**2020**	**2030**	**2050**
Dispatchable (output) (%)	77.0%	69.2%	41.3%	28.0%
Base-load (nuclear) (output) (%)	17.4%	15.6%	19.8%	36.5%
Intermittent (output) (%)	5.6%	15.2%	38.9%	35.5%
Capacity (GW)	99.9	115.0	155.0	200.0
Output (TWh)	368.3	430.0	560.0	830.0
Ave cost (p/kWh)	6.8	8.0	9.1	9.2
Ave cost with 10% demand reduction (p/kWh)	N/A	7.7	8.9	8.8
Total cost (£m/yr)	24,940.8	34,606.1	51,166.6	76,115.9
Total cost with 10% demand reduction (£m/yr)	N/A	29,940.0	44,705.8	65,569.6
Ave benefit of 10% demand reduction (p/kWh)	N/A	10.9	11.5	12.7
Emissions (gCO_2/kWh)	513.8	250.0	100.0	50.0
Shannon-Weiner Index	1.696	1.964	1.938	1.810

3.5.2.1 Optimization 2020

The optimization software was able to find a solution which satisfied all the constraints and optimality conditions.

115GW total capacity, 430TWh annual output and system emissions of 250gCO$_2$/kWh are achieved at a unit cost of 8.0p/kWh and a total annual cost of £34,606.1m. The Shannon-Weiner index is 1.964. The optimized solution screenshot is shown in Figure 3.7.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	**Generation Mix Optimization - 2020**																					
2																						
3	**Technology**	**Capacity**					**Cost**										**Emissions**		**Shannon-Weiner**			
4		Installed	Installed	PLF	Output pa	Output	Capital	Devt	Op life	Capital	Fixed	Var O&M	Fuel	Carbon	Total	Cost	(kgCO2/	Total	Number	Proportion	ln(pi)	Pi*ln(pi)
5	**Dispatchable**	(GW)	(%)	(%)	(TWh)	(%)	(£/kW)	(yrs)	(yrs)	(£m/yr)	(£/kW/yr)	(£/MWh)	(£/MWh)	(£/MWh)	(£m/yr)	(p/kWh)	MWh)	(mtCO2)		(Pi)		
6	Coal ASC	6.3	5.5	91.9	50.8	11.8	2,213.7	13.0	20	1,641.1	79.9	2.2	26.0	17.5	4,466.0	8.8	972	49.4	50.8	0.118	-2.136	-0.252
7	Coal ASC + CCS	0.0	0.0	50.1	0.0	0.0	3,581.7	13.0	20	0.0	120.7	4.7	37.5	24.9	0.0	0.0	292	0.0	0.0	0.000	0.000	0.000
8	Coal IGCC	0.0	0.0	51.6	0.0	0.0	4,064.2	12.0	20	0.0	154.5	3.4	26.5	14.8	0.0	0.0	823	0.0	0.0	0.000	0.000	0.000
9	Coal IGCC +CCS	0.0	0.0	50.7	0.0	0.0	4,780.5	13.0	20	0.0	180.2	4.6	36.9	24.0	0.0	0.0	247	0.0	0.0	0.000	0.000	0.000
10	Gas (CCGT)	35.1	30.6	42.3	130.0	30.2	496.4	4.0	35	1,808.4	25.8	2.3	59.9	7.4	11,765.0	9.0	411	53.4	130.0	0.302	-1.196	-0.362
11	Gas with CCS	0.0	0.0	51.5	0.0	0.0	2,172.9	12.5	20	0.0	154.5	3.6	82.9	24.0	0.0	0.0	245	0.0	0.0	0.000	0.000	0.000
12	CHP (renewables)	15.0	13.0	60.0	78.8	18.3	611.8	5.0	30	973.4	30.6	2.3	40.0	0.5	4,802.8	6.1	25	2.0	78.8	0.183	-1.696	-0.311
13	CHP (other)	0.0	0.0	0.0	0.0	0.0	509.8	4.0	35	0.0	30.6	2.3	59.9	10.0	0.0	0.0	553	0.0	0.0	0.000	0.000	0.000
14	Oil	0.0	0.0	52.3	0.0	0.0	1,000.0	5.0	25	0.0	50.0	2.5	75.0	11.8	0.0	0.0	657	0.0	0.0	0.000	0.000	0.000
15	Hydro	2.0	1.7	36.5	6.4	1.5	3,153.0	5.0	100	630.6	44.0	0.0	0.0	0.2	720.0	11.3	12	0.1	6.4	0.015	-4.208	-0.063
16	Biomass	5.0	4.3	60.0	26.3	6.1	1,312.9	5.0	30	696.3	48.1	4.0	40.0	0.3	2,100.0	8.0	15	0.4	26.3	0.061	-2.795	-0.171
17	Storage - pumped	4.0	3.5	15.0	5.3	1.2	1,000.0	5.0	100	400.0	10.0	2.5	60.0	0.2	769.7	14.6	12	0.1	5.3	0.012	-4.404	-0.054
18	Storage - other	0.0	0.0	15.0	0.0	0.0	3,000.0	5.0	25	0.0	50.0	2.5	0.0	0.2	0.0	0.0	12	0.0	0.0	0.000	0.000	0.000
19	Gas turbines and oil en	4.0	3.5	0.0	0.0	0.0	650.0	5.0	25	286.4	50.0	2.5	60.0	11.8	486.4	0.0	657	0.0	0.0	0.000	0.000	0.000
20	Pumping for PS																					
21		71.4	62.1		297.6	69.2																
22	**Non-Dispatchable**																					
23	Nuclear	9.6	8.3	80.0	67.1	15.6	1,000.0	10.0	60	960.0	65.4	2.1	5.3	0.2	2,096.4	3.1	12	0.8	67.1	0.156	-1.858	-0.290
24	Wind - on-shore	13.0	11.3	27.7	31.5	7.3	1,130.0	5.5	20	1,725.5	44.6	5.0	0.0	0.2	2,468.1	7.8	9	0.3	31.5	0.073	-2.612	-0.192
25	Wind - off-shore	6.6	5.7	32.5	18.8	4.4	2,370.0	7.0	24	1,737.6	115.8	2.0	0.0	0.4	2,545.4	13.6	22	0.4	18.8	0.044	-3.132	-0.137
26	Wind - off-shore (R3)	0.9	0.8	35.0	2.8	0.6	2,505.0	7.0	24	250.9	155.2	7.0	0.0	0.4	411.0	14.9	22	0.1	2.8	0.006	-5.049	-0.032
27	Wave	0.0	0.0	36.5	0.0	0.0	4,830.0	5.0	20	0.0	97.8	0.0	0.0	0.4	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
28	Tidal	0.0	0.0	18.8	0.0	0.0	3,488.4	5.0	120	0.0	40.0	0.0	0.0	0.4	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
29	Solar PV	13.5	11.7	10.4	12.3	2.9	1,089.0	5.0	25	1,619.6	25.5	0.0	0.0	0.9	1,975.2	16.1	51	0.6	12.3	0.029	-3.554	-0.102
30																						
31																						
32		43.6	37.9		132.4	30.8																
33																						
34	Interconnector					0.0								0.0		0.0			0.0	0.000	0.000	0.000
35	Demand side	0.0	0.0	100.0	0.0	0.0								0.0		0.0			0.0	0.000	0.000	0.000
36	Microgen	0.0	0.0	15.0	0.0	0.0	5000	5.0	20.0	0.0	20.0	0.0	0.0	0.4	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
37																						
38	**Totals**	**115.0**	**100.0**	**%**	**430.0**	**100.0**									**£34,606.1**	**8.0**		**107.5**	430.0	1.000	0.000	-1.964
39																						
40	**Total Renewables**	**56.0**	**48.7%**		**176.9**	**41.1%**												**250.0**				**1.964**
41	**Total Low Carbon**	**69.6**	**60.5%**		**249.2**	**57.9%**												gCO2/kWh				
42																						
43	**Targets**																					
44	Total capacity	**115**	GW		Renewables		**30%**	min		Max output/tech		**50**	%									
45	Total output	**430**	TWh/yr		Low carbon		**40%**	min		Max non-dispatch		**50**	%									
46	Average emission	**250**	gCO2/kWh		Carbon Price		**£18**	/tonne		Shannon-Weiner		**1.500**										
47																						

Figure 3.7 2020 Optimization screenshot

Generating capacity for 2020 is shown on Table 3.8.

Table 3.9 2020 generating capacity

Technology	Capacity (GW)
Coal	6.3
Gas (CCGT)	35.1
CHP (renewables)	15.0
Hydro	2.0
Biomass	5.0
Pumped storage	4.0
Gas turbines and oil engines	4.6
Nuclear	9.6
On-shore wind	13.0
Off-shore wind	6.6
Off-shore wind (round 3)	0.9
Solar PV	13.5

The capacity and output results are shown in Figure 3.8.

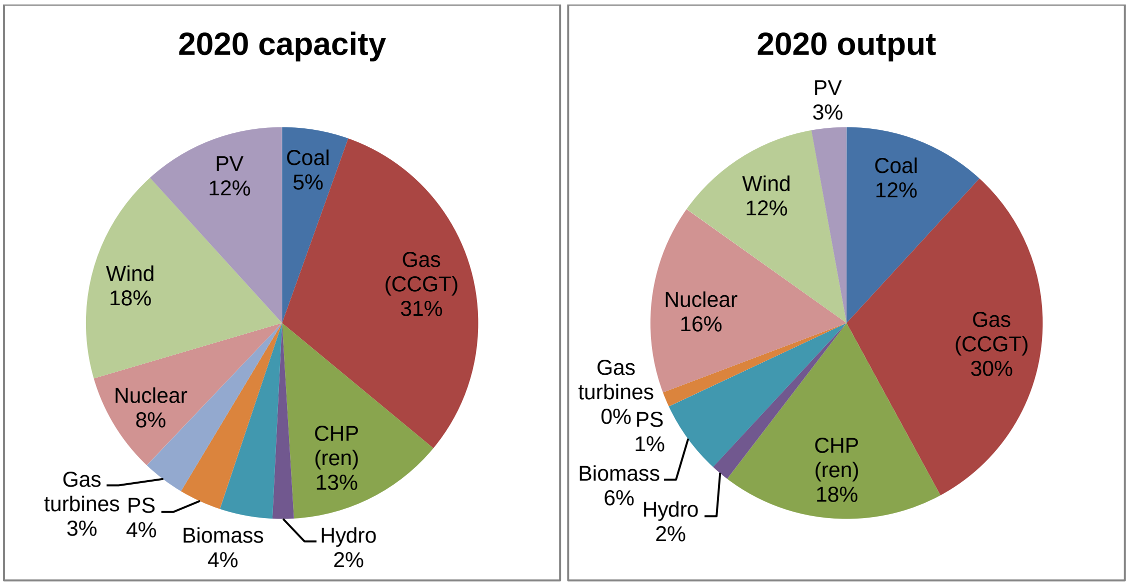


Figure 3.8 2020 capacity and annual output

PLF maximum constraint limits are reached on all technologies except for gas (CCGT), which is reduced from 93.7% to 42.3%, and gas turbines and oil engines, which is reduced from 90.0% to 0.0%. This is due to the relatively low capital cost of these plants compared with other technologies, allowing them to run at lower load factors economically in order to satisfy the overall capacity target.

Gas CCGT is at the maximum capacity limit and CHP (renewables) and biomass capacities combined are limited to 20GW by the constraint imposed on feedstock availability. Hydro and pumped storage capacities are at the maximum amounts set by the constraints and reflect existing and identified new capacity.

Nuclear capacity is made up of existing plants, including 5.9GW of deferred retirals, but no new capacity. On-shore wind capacity is at the maximum constraint of 13GW, off-shore at 6.6GW and R3 at the minimum constraint level of 0.9GW. Solar PV, whilst more expensive than other technologies, is installed in order to achieve the total capacity and output targets.

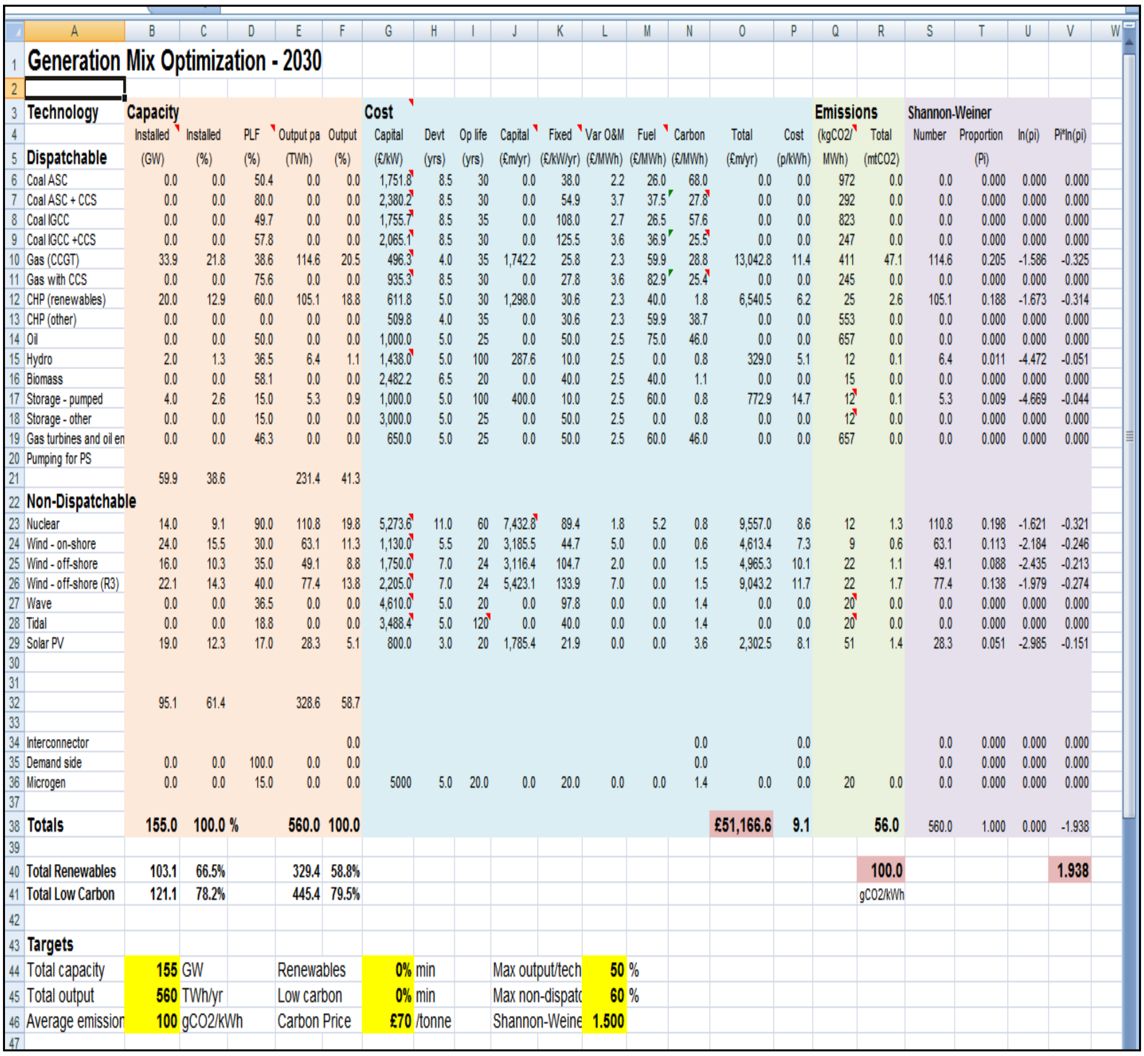
The emissions target of 250gCO_2/kWh is met with coal being the highest emitting technology at 972gCO_2/kWh.

Renewables account for 48.7% of capacity and 41.1% of output, and low carbon generators account for 60.5% and 57.9% respectively. The dispatchable element is 62.1% of capacity and 69.2% of output compared with 79.4% and 77.0% in 2012.

3.5.2.2 Optimization 2030

The optimization software was able to find a solution which satisfied all the constraints and optimality conditions. This, however, was only achieved by relaxing the maximum non-dispatchable element from 50% to 60%. Without this relaxation, Solver was unable to find a solution which also satisfied the emissions target of 100gCO_2/kWh.

155GW total capacity, 560TWh annual output and system emissions of 100.0gCO_2/kWh are achieved at a unit cost of 9.1p/kWh and a total annual cost of £51,166.6m. The Shannon-Weiner index is 1.938. The optimized solution screenshot is shown in Figure 3.9.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	**Generation Mix Optimization - 2030**																					
2																						
3	**Technology**	**Capacity**					**Cost**										**Emissions**		**Shannon-Weiner**			
4		Installed	Installed	PLF	Output pa	Output	Capital	Devt	Op life	Capital	Fixed	Var O&M	Fuel	Carbon	Total	Cost	(kgCO2/	Total	Number	Proportion	ln(pi)	Pi*ln(pi)
5	**Dispatchable**	(GW)	(%)	(%)	(TWh)	(%)	(£/kW)	(yrs)	(yrs)	(£m/yr)	(£/kW/yr)	(£/MWh)	(£/MWh)	(£/MWh)	(£m/yr)	(p/kWh)	MWh)	(mtCO2)		(Pi)		
6	Coal ASC	0.0	0.0	50.4	0.0	0.0	1,751.8	8.5	30	0.0	38.0	2.2	26.0	68.0	0.0	0.0	972	0.0	0.0	0.000	0.000	0.000
7	Coal ASC + CCS	0.0	0.0	80.0	0.0	0.0	2,380.2	8.5	30	0.0	54.9	3.7	37.5	27.8	0.0	0.0	292	0.0	0.0	0.000	0.000	0.000
8	Coal IGCC	0.0	0.0	49.7	0.0	0.0	1,755.7	8.5	35	0.0	108.0	2.7	26.5	57.6	0.0	0.0	823	0.0	0.0	0.000	0.000	0.000
9	Coal IGCC +CCS	0.0	0.0	57.8	0.0	0.0	2,065.1	8.5	30	0.0	125.5	3.6	36.9	25.5	0.0	0.0	247	0.0	0.0	0.000	0.000	0.000
10	Gas (CCGT)	33.9	21.8	38.6	114.6	20.5	496.3	4.0	35	1,742.2	25.8	2.3	59.9	28.8	13,042.8	11.4	411	47.1	114.6	0.205	-1.586	-0.325
11	Gas with CCS	0.0	0.0	75.6	0.0	0.0	935.3	8.5	30	0.0	27.8	3.6	82.9	25.4	0.0	0.0	245	0.0	0.0	0.000	0.000	0.000
12	CHP (renewables)	20.0	12.9	60.0	105.1	18.8	611.8	5.0	30	1,298.0	30.6	2.3	40.0	1.8	6,540.5	6.2	25	2.6	105.1	0.188	-1.673	-0.314
13	CHP (other)	0.0	0.0	0.0	0.0	0.0	509.8	4.0	35	0.0	30.6	2.3	59.9	38.7	0.0	0.0	553	0.0	0.0	0.000	0.000	0.000
14	Oil	0.0	0.0	50.0	0.0	0.0	1,000.0	5.0	25	0.0	50.0	2.5	75.0	46.0	0.0	0.0	657	0.0	0.0	0.000	0.000	0.000
15	Hydro	2.0	1.3	36.5	6.4	1.1	1,438.0	5.0	100	287.6	10.0	2.5	0.0	0.8	329.0	5.1	12	0.1	6.4	0.011	-4.472	-0.051
16	Biomass	0.0	0.0	58.1	0.0	0.0	2,482.2	6.5	20	0.0	40.0	2.5	40.0	1.1	0.0	0.0	15	0.0	0.0	0.000	0.000	0.000
17	Storage - pumped	4.0	2.6	15.0	5.3	0.9	1,000.0	5.0	100	400.0	10.0	2.5	60.0	0.8	772.9	14.7	12	0.1	5.3	0.009	-4.669	-0.044
18	Storage - other	0.0	0.0	15.0	0.0	0.0	3,000.0	5.0	25	0.0	50.0	2.5	0.0	0.8	0.0	0.0	12	0.0	0.0	0.000	0.000	0.000
19	Gas turbines and oil en	0.0	0.0	46.3	0.0	0.0	650.0	5.0	25	0.0	50.0	2.5	60.0	46.0	0.0	0.0	657	0.0	0.0	0.000	0.000	0.000
20	Pumping for PS																					
21		59.9	38.6		231.4	41.3																
22	**Non-Dispatchable**																					
23	Nuclear	14.0	9.1	90.0	110.8	19.8	5,273.6	11.0	60	7,432.8	89.4	1.8	5.2	0.8	9,557.0	8.6	12	1.3	110.8	0.198	-1.621	-0.321
24	Wind - on-shore	24.0	15.5	30.0	63.1	11.3	1,130.0	5.5	20	3,185.5	44.7	5.0	0.0	0.6	4,613.4	7.3	9	0.6	63.1	0.113	-2.184	-0.246
25	Wind - off-shore	16.0	10.3	35.0	49.1	8.8	1,750.0	7.0	24	3,116.4	104.7	2.0	0.0	1.5	4,965.3	10.1	22	1.1	49.1	0.088	-2.435	-0.213
26	Wind - off-shore (R3)	22.1	14.3	40.0	77.4	13.8	2,205.0	7.0	24	5,423.1	133.9	7.0	0.0	1.5	9,043.2	11.7	22	1.7	77.4	0.138	-1.979	-0.274
27	Wave	0.0	0.0	36.5	0.0	0.0	4,610.0	5.0	20	0.0	97.8	0.0	0.0	1.4	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
28	Tidal	0.0	0.0	18.8	0.0	0.0	3,488.4	5.0	120	0.0	40.0	0.0	0.0	1.4	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
29	Solar PV	19.0	12.3	17.0	28.3	5.1	800.0	3.0	20	1,785.4	21.9	0.0	0.0	3.6	2,302.5	8.1	51	1.4	28.3	0.051	-2.985	-0.151
30																						
31																						
32		95.1	61.4		328.6	58.7																
33																						
34	Interconnector					0.0								0.0		0.0			0.0	0.000	0.000	0.000
35	Demand side	0.0	0.0	100.0	0.0	0.0								0.0		0.0			0.0	0.000	0.000	0.000
36	Microgen	0.0	0.0	15.0	0.0	0.0	5000	5.0	20.0	0.0	20.0	0.0	0.0	1.4	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
37																						
38	**Totals**	**155.0**	**100.0 %**		**560.0**	**100.0**									**£51,166.6**	**9.1**		**56.0**	560.0	1.000	0.000	-1.938
39																						
40	**Total Renewables**	**103.1**	**66.5%**		**329.4**	**58.8%**												**100.0**				**1.938**
41	**Total Low Carbon**	**121.1**	**78.2%**		**445.4**	**79.5%**												gCO2/kWh				
42																						
43	**Targets**																					
44	Total capacity	**155**	GW		Renewables		**0%**	min		Max output/tech		**50**	%									
45	Total output	**560**	TWh/yr		Low carbon		**0%**	min		Max non-dispatc		**60**	%									
46	Average emission	**100**	gCO2/kWh		Carbon Price		**£70**	/tonne		Shannon-Weine		**1.500**										
47																						

Figure 3.9 2030 Optimization screenshot

Generating capacity for 2030 is shown on Table 3.10.

Table 3.10 2030 generating capacity

Technology	Capacity (GW)
Gas (CCGT)	14.0
CHP (renewables)	20.0
Hydro	2.0
Pumped storage	4.0
Nuclear	14.0
On-shore wind	24.0
Off-shore wind	16.0
Off-shore wind (round 3)	22.1
Solar PV	19.0

The capacity and output results are shown in Figure 3.10.

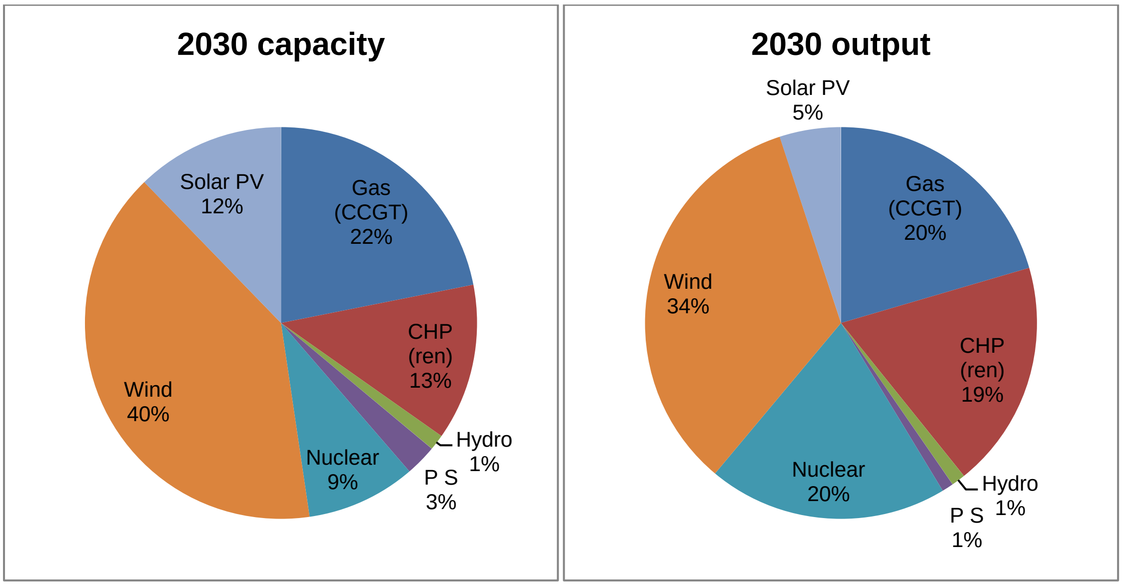


Figure 3.10 2030 capacity and annual output

CHP (renewables) is limited to 20GW by the constraint imposed on feedstock availability and Hydro capacity is at the maximum amount set and pumped storage at current levels.

Nuclear capacity is made up of plants in 2020 less retirals and 5 new 1.6GW reactors. On-shore wind and off-shore wind (not R3), and solar PV capacity is limited by the maximum capacity constraint.

The emissions target of 100gCO_2/kWh is met with the highest emitting technology being gas (CCGT) at 411gCO_2/kWh.

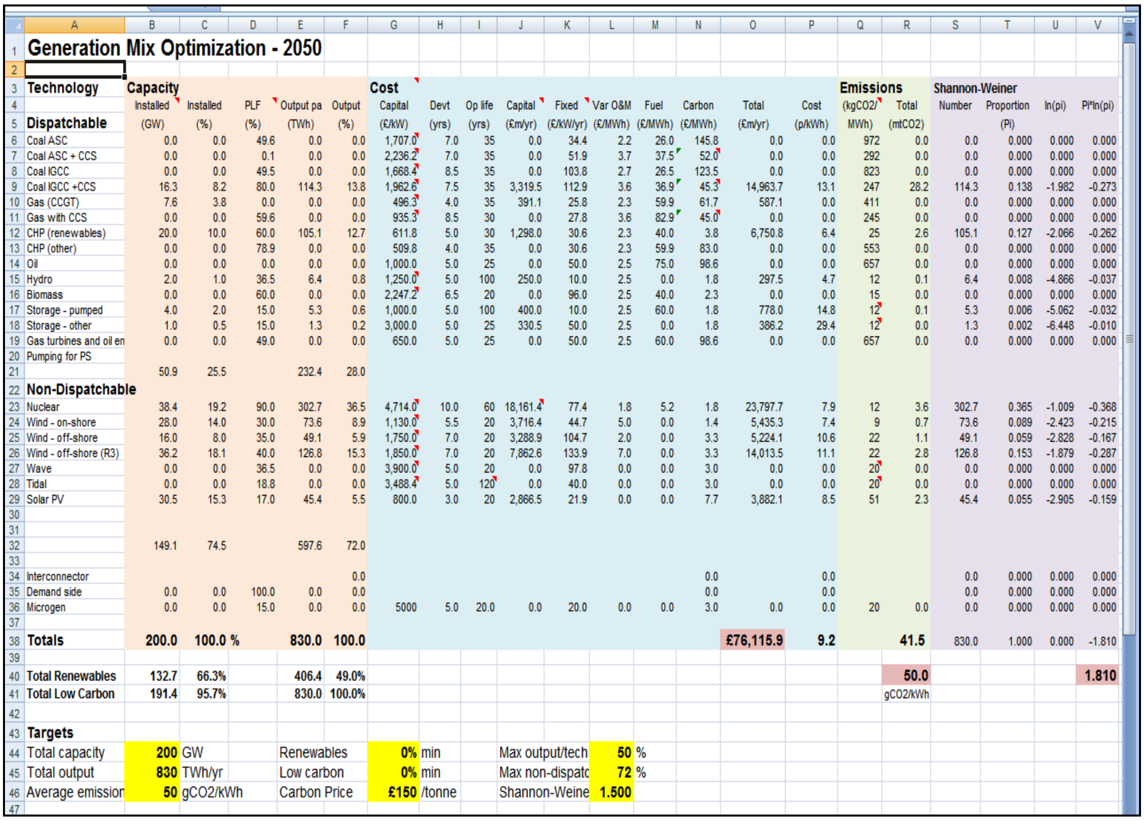
Renewables account for 66.5% of capacity and 58.8% of output, and low carbon generators account for 78.2% and 79.5% respectively. The dispatchable element is 38.6% of capacity and 41.3% of output compared with 79.4% and 77.0% in 2012.

3.5.2.3 Optimization 2050

The optimization software was able to find a solution which satisfied all the constraints and optimality conditions. This, however, was only achieved by relaxing the maximum non-dispatchable element further to 72%. Without this relaxation, Solver was unable to find a solution which also satisfied the emissions target of 50gCO_2/kWh.

200GW total capacity, 830TWh annual output and system emissions of 50.0gCO_2/kWh are achieved at a unit cost of 9.2p/kWh and a total annual cost of £76,115.9m. The

Shannon-Weiner index is 1.810. The optimized solution screenshot is shown in Figure 3.11.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	**Generation Mix Optimization - 2050**																					
2																						
3	**Technology**	**Capacity**					**Cost**										**Emissions**		**Shannon-Weiner**			
4		Installed	Installed	PLF	Output pa	Output	Capital	Devt	Op life	Capital	Fixed	Var O&M	Fuel	Carbon	Total	Cost	(kgCO2/	Total	Number	Proportion	ln(pi)	Pi*ln(pi)
5	**Dispatchable**	(GW)	(%)	(%)	(TWh)	(%)	(£/kW)	(yrs)	(yrs)	(£m/yr)	(£/kW/yr)	(£/MWh)	(£/MWh)	(£/MWh)	(£m/yr)	(p/kWh)	MWh)	(mtCO2)		(Pi)		
6	Coal ASC	0.0	0.0	49.6	0.0	0.0	1,707.0	7.0	35	0.0	34.4	2.2	26.0	145.8	0.0	0.0	972	0.0	0.0	0.000	0.000	0.000
7	Coal ASC + CCS	0.0	0.0	0.1	0.0	0.0	2,236.2	7.0	35	0.0	51.9	3.7	37.5	52.0	0.0	0.0	292	0.0	0.0	0.000	0.000	0.000
8	Coal IGCC	0.0	0.0	49.5	0.0	0.0	1,668.4	8.5	35	0.0	103.8	2.7	26.5	123.5	0.0	0.0	823	0.0	0.0	0.000	0.000	0.000
9	Coal IGCC +CCS	16.3	8.2	80.0	114.3	13.8	1,962.6	7.5	35	3,319.5	112.9	3.6	36.9	45.3	14,963.7	13.1	247	28.2	114.3	0.138	-1.982	-0.273
10	Gas (CCGT)	7.6	3.8	0.0	0.0	0.0	496.3	4.0	35	391.1	25.8	2.3	59.9	61.7	587.1	0.0	411	0.0	0.0	0.000	0.000	0.000
11	Gas with CCS	0.0	0.0	59.6	0.0	0.0	935.3	8.5	30	0.0	27.8	3.6	82.9	45.0	0.0	0.0	245	0.0	0.0	0.000	0.000	0.000
12	CHP (renewables)	20.0	10.0	60.0	105.1	12.7	611.8	5.0	30	1,298.0	30.6	2.3	40.0	3.8	6,750.8	6.4	25	2.6	105.1	0.127	-2.066	-0.262
13	CHP (other)	0.0	0.0	78.9	0.0	0.0	509.8	4.0	35	0.0	30.6	2.3	59.9	83.0	0.0	0.0	553	0.0	0.0	0.000	0.000	0.000
14	Oil	0.0	0.0	0.0	0.0	0.0	1,000.0	5.0	25	0.0	50.0	2.5	75.0	98.6	0.0	0.0	657	0.0	0.0	0.000	0.000	0.000
15	Hydro	2.0	1.0	36.5	6.4	0.8	1,250.0	5.0	100	250.0	10.0	2.5	0.0	1.8	297.5	4.7	12	0.1	6.4	0.008	-4.866	-0.037
16	Biomass	0.0	0.0	60.0	0.0	0.0	2,247.2	6.5	20	0.0	96.0	2.5	40.0	2.3	0.0	0.0	15	0.0	0.0	0.000	0.000	0.000
17	Storage - pumped	4.0	2.0	15.0	5.3	0.6	1,000.0	5.0	100	400.0	10.0	2.5	60.0	1.8	778.0	14.8	12	0.1	5.3	0.006	-5.062	-0.032
18	Storage - other	1.0	0.5	15.0	1.3	0.2	3,000.0	5.0	25	330.5	50.0	2.5	0.0	1.8	386.2	29.4	12	0.0	1.3	0.002	-6.448	-0.010
19	Gas turbines and oil en	0.0	0.0	49.0	0.0	0.0	650.0	5.0	25	0.0	50.0	2.5	60.0	98.6	0.0	0.0	657	0.0	0.0	0.000	0.000	0.000
20	Pumping for PS																					
21		50.9	25.5		232.4	28.0																
22	**Non-Dispatchable**																					
23	Nuclear	38.4	19.2	90.0	302.7	36.5	4,714.0	10.0	60	18,161.4	77.4	1.8	5.2	1.8	23,797.7	7.9	12	3.6	302.7	0.365	-1.009	-0.368
24	Wind - on-shore	28.0	14.0	30.0	73.6	8.9	1,130.0	5.5	20	3,716.4	44.7	5.0	0.0	1.4	5,435.3	7.4	9	0.7	73.6	0.089	-2.423	-0.215
25	Wind - off-shore	16.0	8.0	35.0	49.1	5.9	1,750.0	7.0	20	3,288.9	104.7	2.0	0.0	3.3	5,224.1	10.6	22	1.1	49.1	0.059	-2.828	-0.167
26	Wind - off-shore (R3)	36.2	18.1	40.0	126.8	15.3	1,850.0	7.0	20	7,862.6	133.9	7.0	0.0	3.3	14,013.5	11.1	22	2.8	126.8	0.153	-1.879	-0.287
27	Wave	0.0	0.0	36.5	0.0	0.0	3,900.0	5.0	20	0.0	97.8	0.0	0.0	3.0	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
28	Tidal	0.0	0.0	18.8	0.0	0.0	3,488.4	5.0	120	0.0	40.0	0.0	0.0	3.0	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
29	Solar PV	30.5	15.3	17.0	45.4	5.5	800.0	3.0	20	2,866.5	21.9	0.0	0.0	7.7	3,882.1	8.5	51	2.3	45.4	0.055	-2.905	-0.159
30																						
31																						
32		149.1	74.5		597.6	72.0																
33																						
34	Interconnector					0.0								0.0		0.0			0.0	0.000	0.000	0.000
35	Demand side	0.0	0.0	100.0	0.0	0.0								0.0		0.0			0.0	0.000	0.000	0.000
36	Microgen	0.0	0.0	15.0	0.0	0.0	5000	5.0	20.0	0.0	20.0	0.0	0.0	3.0	0.0	0.0	20	0.0	0.0	0.000	0.000	0.000
37																						
38	**Totals**	**200.0**	**100.0 %**		**830.0**	**100.0**									**£76,115.9**	**9.2**		**41.5**	830.0	1.000	0.000	-1.810
39																						
40	**Total Renewables**	**132.7**	**66.3%**		**406.4**	**49.0%**												**50.0**				**1.810**
41	**Total Low Carbon**	**191.4**	**95.7%**		**830.0**	**100.0%**												gCO2/kWh				
42																						
43	**Targets**																					
44	Total capacity	**200**	GW		Renewables		**0%**	min		Max output/tech		**50**	%									
45	Total output	**830**	TWh/yr		Low carbon		**0%**	min		Max non-dispatc		**72**	%									
46	Average emission	**50**	gCO2/kWh		Carbon Price		**£150**	/tonne		Shannon-Weine		**1.500**										
47																						

Figure 3.11 2050 Optimization screenshot

Generating capacity for 2050 is shown on Table 3.11.

Table 3.11 2050 generating capacity

Technology	Capacity (GW)
Coal IGCC with CCS	16.3
Gas CCGT	7.6
CHP (renewables)	20.0
Hydro	2.0
Pumped storage	4.0
Storage (other)	1.0
Nuclear	38.4
On-shore wind	28.0
Off-shore wind	16.0
Off-shore wind (round 3)	36.2
Solar PV	30.5

The capacity and output results are shown in Figure 3.12.

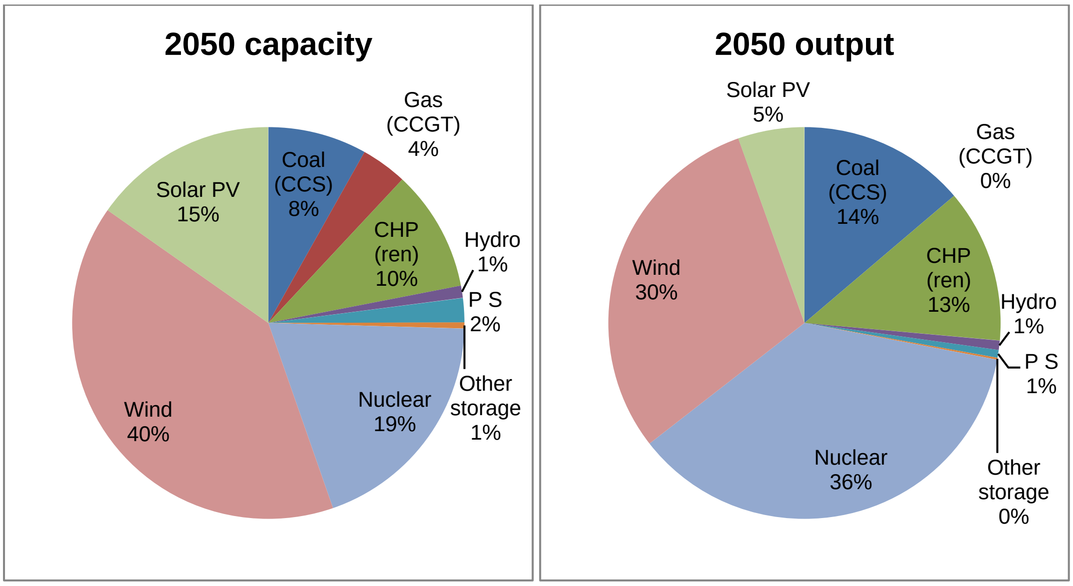


Figure 3.12 2050 capacity and annual output

Gas (CCGT) accounts for 4% of the capacity but does not contribute to annual output. This is due to the relatively low capital costs of gas plants relative to other technologies and is required in order to satisfy the overall capacity target. CHP (renewables) is limited to 20GW by the constraint imposed on feedstock availability and Hydro capacity is at the maximum capacity constraint.

Nuclear capacity is made up of plants in 2030 less retirals and 24 new 1.6GW reactors. On-shore and off-shore wind (not R3) capacities are at the maximum capacity constraint levels.

The emissions target of 50gCO_2/kWh is met and the highest emitting technology is coal IGCC with CCS at 247gCO_2/kWh, though if gas (CCGT) is utilised it would emit 411gCO_2/kWh.

Renewables account for 66.3% of capacity and 49.0% of output, and low carbon generators, including coal with CCS, account for 96.2% of capacity (gas not classified as low carbon) and 100.0% of output. The dispatchable element is 25.5% of capacity and 28.0% of output compared with 79.4% and 77.0% in 2012.

3.5.3 Discussion

The model, by definition, is limited in scope and only addresses annual output (energy). Notwithstanding minimum overall capacity requirements, it does not address ongoing real time capacity issues relating to maintaining a continuous balance between supply and demand.

The assumptions used in the model have been drawn from plausible sources. However, these assumptions can be replaced with equally plausible alternatives resulting in different outcomes.

One of the most significant aspects of the results is the change in supply characteristics from a mix which is substantially dispatchable (79.4% of capacity and 77.0% of output in 2012) to a mix with high levels of non-dispatchable generation, particularly from 2030 on. Non-dispatchable levels of 61.4% capacity and 58.7% output in 2030, will create significant challenges to maintaining a continuous balance between supply and demand, particularly where 52.4% of the capacity and 38.9% of the output are from intermittent sources such as wind and solar. This will also affect the operation of the system in other ways, such as elements of frequency control which currently relies on large thermal plants to provide system inertia (stored rotating energy) [48].

The average unit cost (p/kWh) of supply increases by 34% between 2012 and 2030 (6.8p/kWh to 9.1p/kWh), partly as a result of an increase in higher cost renewables and also due to the increase of the carbon price floor from approx. £10/tonne in 2012 to £70/tonne in 2030. Unit cost increases are, however, limited due to the reduction in capital costs of developing technologies as they move from first of a kind (FOAK) to nth of a kind (NOAK) levels. Improvements in plant load factors of renewable technologies also help to limit unit cost increases.

Another significant aspect of the results is the impact on costs (and emissions) through reducing annual demand (capacity and output). The effect in 2030 is to create a benefit of 11.5p/kWh saved, where annual capacity and output is reduced by 10%.

The costs do not include any costs involved in the transmission and distribution system, arising from an increase in distributed generation, or balancing costs, such as maintaining an increased short term operating reserve.

Chapter 4

Flexible domestic electricity demand

Summary:

This chapter examines GB domestic electricity demand and the extent to which this is flexible. It considers demand by category and sub-category, and gives projections of annual domestic electricity demand to 2030. It also provides daily load profiles for the flexible categories of electric space and water heating, cold appliances and wet appliances, across two sample days in 2030.

It is based on a paper presented to the International Conference on Applied Energy, *July 1 – 4 2013 in Pretoria, South Africa, entitled* “Flexible demand in the GB domestic electricity sector in 2030” *(Drysdale B, Wu J, Jenkins N (2013)). An adaptation of the paper has been accepted for publication by Applied Energy.*

4.1 Introduction

4.1.1 Electricity generation and demand side management (DSM)

Projected changes to the combination of generating technologies in the UK, partly as a result of efforts to meet climate change emissions reduction targets, will result in less dispatchable (controllable) generating plant available in the future for use in maintaining a balance between supply and demand (Figure 4.1).

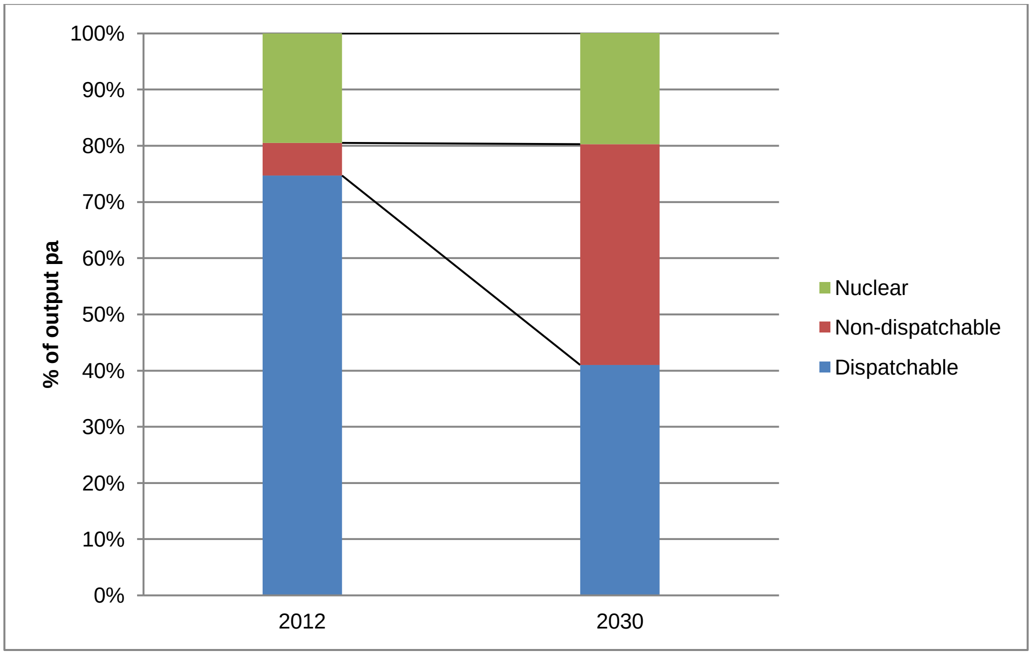


Figure 4.1 Energy output from generating technology categories in 2012 and 2030 [1] [2]

This will create opportunities for demand side management (DSM) to play a more active part in maintaining a balance. Elements of DSM described in [3] are demand response (flexibility), demand management (efficiency/reduction), and distributed generation.

The effective exploitation of flexible demand requires loads to be identifiable and accessible, appropriate for the service being called upon i.e. of sufficient size, speed of response and duration, and changes to the loads e.g. load shedding/shifting, must be acceptable to consumers i.e. consumers need to have appropriate incentives to participate.

The Department of Energy and Climate Change (DECC) recognizes the importance of DSM to the future electricity system as evidenced by the development of policies, such as the smart meter roll out [4] and the inclusion of demand in the design of the capacity market within the electricity market reform package [5]. These, however, tend to focus on demand reduction, in the case of the smart meter roll out, and larger, non-domestic, consumers, in the case of engagement with the capacity market. The System Operator (National Grid) and Ofgem also recognize that the demand side has a part to play in maintaining a balance between supply and demand, as evidenced by National Grid's 2013 consultation on additional balancing services and the proposed introduction of a Demand Side Balancing Reserve [6], and Ofgem's 2013 consultation on creating the right environment for demand-side response [7].

4.1.2 Domestic electricity demand in 2012

Electricity consumption in the UK in 2012 amounted to 318TWh, not including electricity used by the power industry and network losses [8], with domestic consumption amounting to approx. 36% of the total. Scenarios of future demand, including National Grid's UK Future Energy Scenarios (2013) [9] and McKinsey's 2012 report for DECC on Capturing the full electricity efficiency potential of the UK [10], indicate changes in overall demand levels. The relative size of the domestic sector, however, remains broadly in line with current consumption (34% in 2030 [10] from 36% in 2012 [8]), as shown in Figure 4.2.

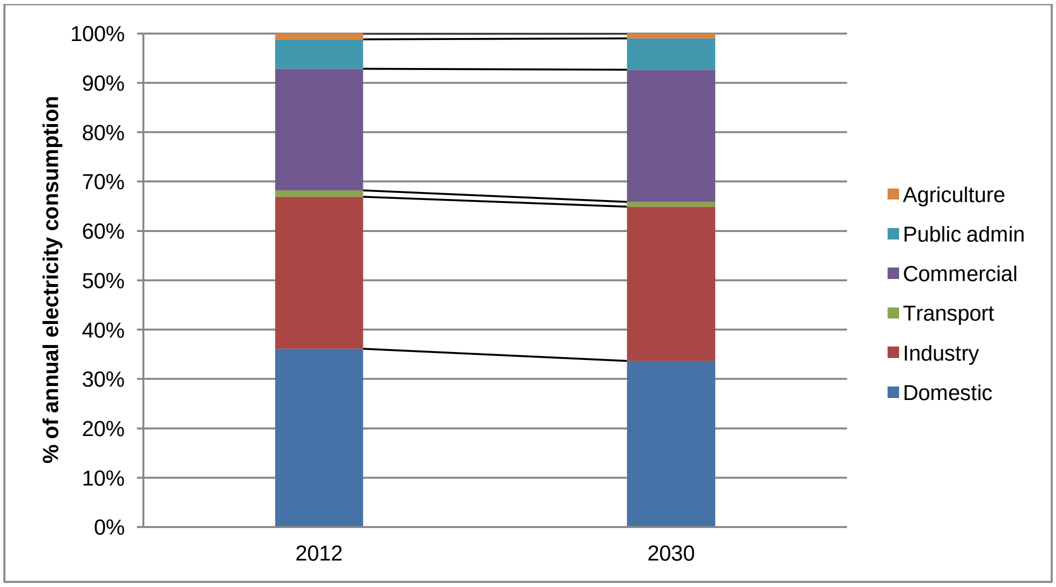


Figure 4.2 UK electricity consumption by sector (2012 and 2030) [8 & 10]

UK domestic electricity consumption, including electric space and water heating (ESWH), is significant in terms of overall UK consumption and it is, therefore, worth exploring the potential for DSM in this sector.

Studies, such as the Frontier Economics and Sustainability First report for DECC in 2012 [11], considering changes in timing of domestic electricity consumption, and the Sustainability First GB Electricity Demand report in 2012 [12], examining GB electricity demand in 2010 and 2025 and the amount of potential shiftable load across all sectors, indicate there is an important role for the domestic sector to contribute to DSM. The Frontier Economics and Sustainability First report shows day-in day-out reductions of 0 - 22% and critical peak reductions of 5 – 38% of the domestic load, whilst the Sustainability First GB Electricity Demand report shows peak reductions of 29 – 40% with the domestic sector accounting for 40 – 50% of the shiftable load.

UK domestic electricity consumption in 2012 amounted to 116.1TWh [13] divided between lighting and appliances (72%), space heating (21%) and water heating (7%), as shown in Figure 4.3.

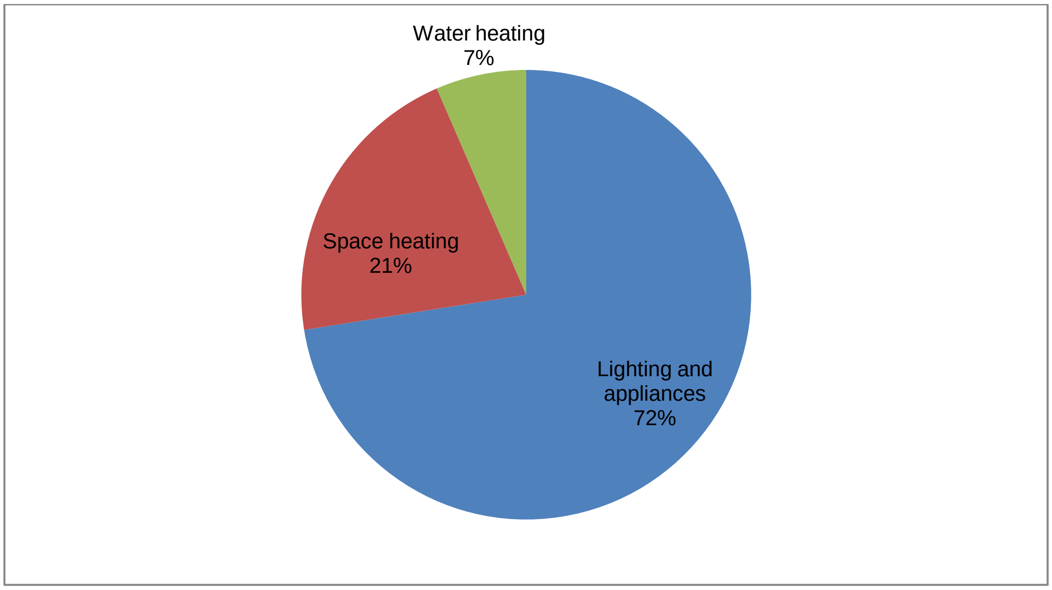


Figure 4.3 UK annual domestic electricity consumption in 2012 [13]

The majority of domestic consumption in 2012 is in the lighting and appliances section (72%). The allocation of demand in 2012 between the different lighting and appliances categories is shown in Figure 4.4.

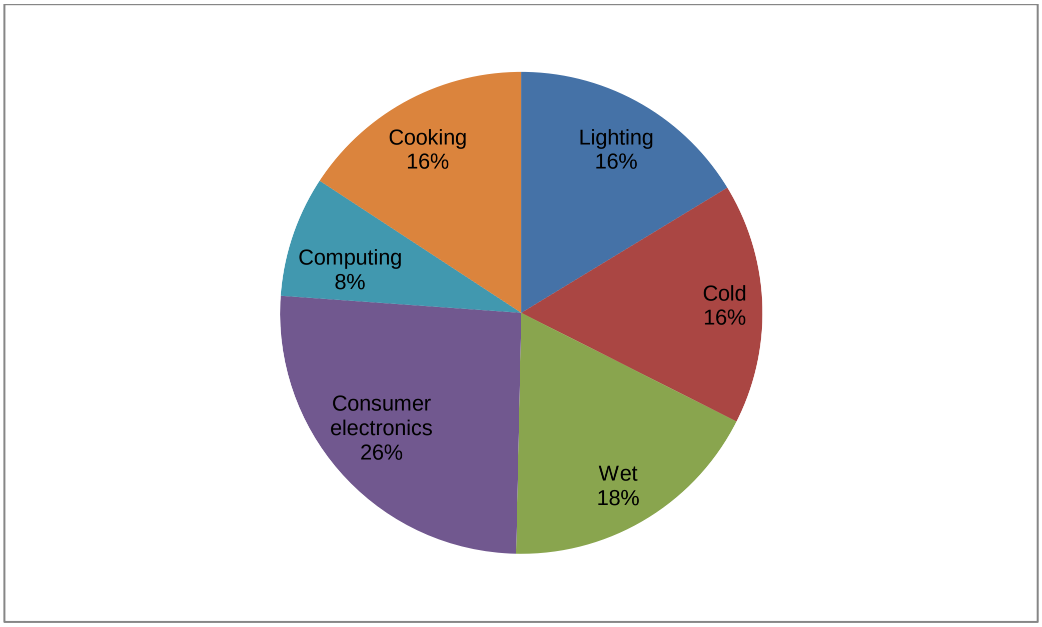


Figure 4.4 UK domestic electricity consumption – lighting and appliances in 2012 [14]

Lighting and appliances are further sub-divided into sub-categories, as shown in Table 4.1.

Table 4.1 Lighting and appliance categories and sub-categories

Category	**Sub-Category**				
Lighting	Standard light bulb (SLB)	Halogen	Fluorescent strip lighting	Energy saving light bulb (ESB)	LED
Cold appliances	Chest freezer	Fridge-freezer	Refrigerator	Upright freezer	
Wet appliances	Washing machine	Washer dryer	Dishwasher	Tumble dryer	
Consumer electronics	TV	Set top box	DVD/VCR	Games consoles	Power supply units
Home computing	Desktops	Laptops	Monitors	Printers	Multi function devices
Cooking	Electric oven	Electric hob	Microwave	Kettle	

Characteristics of demand vary between the different categories and are related to the spatial and temporal proximity to consumer engagement. Categories, such as lighting and consumer electronics, have an immediate relationship with the consumer whereas other categories, such as wet and cold appliances, can operate with a degree of independence from consumer engagement [15].

4.1.3 Flexible domestic electricity demand

Flexible demand is useful in current and future balancing markets. Current markets include frequency response and short term reserves. Potential future markets include the capacity market [16], and services supporting distribution networks.

The degree of flexibility, i.e. the ability of a load to vary in response to an external signal with minimal disruption to consumer utility, varies between load categories. Appliances that can operate independently from consumers, such as fridges and washing machines, can be more flexible without loss of utility to the consumer. Other appliances, such as televisions and lighting, are less flexible as they are required to be on when the consumer engages with their function. Electric space and water heating (ESWH) and cold appliances have thermal storage properties which allow load to be curtailed, reduced or postponed [17]. They also have the capacity to increase consumption if required by system conditions e.g. surplus of supply or to preload in anticipation of a forthcoming capacity constraint.

This chapter projects annual household electricity consumption from 2012 to 2030 and details daily load profiles for flexible loads, defined as ESWH and cold and wet appliances, for typical summer and winter days in 2030. The projected annual load indicates the total electrical energy consumed by the GB domestic sector per year, and the electrical power load profiles indicate the maximum flexible domestic load from ESWH and cold and wet appliances which may be available for system balancing and other purposes such as load shifting.

Electric vehicle (EV) loads have not been considered due to uncertainty at what level of the distribution network future mass EV loads may be drawn and because the size of the load would overshadow the usefulness and availability of other loads.

4.2 Methodology

4.2.1 Great Britain (GB) and United Kingdom (UK)

The transmission network in GB is operated independently of the network in Northern Ireland, which is part of the all island Irish network, including the Republic of Ireland. However, the primary source of historic appliance consumption data (ECUK) [13] used in this study is expressed in UK terms i.e. GB and Northern Ireland. In order to examine how domestic loads contribute to balancing the GB network, annual consumption per appliance is converted to GB terms at the final stage of analysis.

The total number of households in GB in 2012 was 26.1m which was 97.4% of the total number of UK households [18]. When this is applied on a pro-rata basis to consumption, GB domestic electricity consumption in 2012 was 113.1TWh. Minor differences in demographics forecast by the UK Government's Office for National Statistics [19] show that the number of GB households relative to UK households drops marginally from approximately 97.4% in 2012 to approximately 97.3% in 2030 (32.1m UK households and 31.3m GB households).

4.2.2 Appliance annual electricity consumption

The primary data source used for household appliance consumption is Energy Consumption in the UK (ECUK) [13] tables published by the UK Government's Office for National Statistics. This data allows the calculation of total domestic energy consumption, consumption by fuel type and electricity consumption by appliance type. The July 2013 issue of ECUK gives consumption data in the UK from 1970 to 2012 and, from this data, projections are made to show possible annual consumption figures by appliance type to 2030.

Selected data from Tables 3.05 [20] and 3.10 [14] of the July 2013 issue of ECUK [13] are used in this study to calculate the total annual consumption of electricity for each appliance category and sub-category. Total consumption for each appliance category and sub-category is calculated by multiplying the number of appliances with the annual consumption per appliance. The number of appliances is the number of households multiplied by the number of appliances per household, and the consumption per appliance is appliance efficiency multiplied by usage rates.

Projections of electricity consumption to 2030 for domestic ESWH are based on the Committee of Climate Change, Decarbonising Heat Report [21]. The number of households projection is sourced from the Department for Communities and Local Government Household Projections, United Kingdom, 1961 – 2033 [18] and is used across all appliance categories in this study. The number of appliances per household and the consumption per appliance projections are calculated using extrapolation of the last 10 years of data from ECUK [13]. Flexible demand categories i.e. cold and wet appliances, and cooking appliance projections are calculated with the MS Excel TREND function, using exponential extrapolation of the previous 10 years of data, and assume existing trends will continue with no major technological or behavioural disruptions. Where such disruptions are anticipated, such as in consumer electronics, computing and lighting categories, projections are damped to reduce the risk of large errors [22].

4.2.3 Daily load profiles

Whilst an appreciation of annual appliance demand is useful in understanding the total amount of energy consumed each year by each category, this does not take account of the relationship between instantaneous power demands on generation and network capacity on an ongoing basis.

In order to consider the extent of flexible demand available on an ongoing basis, this study produces typical summer and winter daily demand profiles for ESWH and cold and wet appliances in 2030. The profiles are derived from hourly data from the Household Electricity Survey (HES) [23] and adjusted for changes in household numbers, household composition and changes in annual electricity consumption per appliance. The HES, jointly funded by Defra, DECC and EST, comprised a survey of 251 households in England between May 2010 and July 2011. 26 households were monitored for 1 year and the remainder for periods of 1 month throughout the year [23]. Space heating profiles are based on data for electric central heating (6 no. appliances monitored), circulation pumps (2 no. appliances monitored) and individual heaters (46 no. appliances monitored) [24]. Water heating profiles are based on data for immersion heaters (22 no. appliances monitored) and electric showers (92 no appliances monitored) [25]. Both space heating and water heating profiles were adjusted for seasonal factors [26]. Alternative load profiles are also available from the Customer Led Network Revolution project, funded through the Low Carbon Network Fund [32].

4.3 Projected annual domestic electricity demand in 2030

Results for GB domestic electricity demand in 2030 show an increase in overall demand from 113.1TWh in 2012, to 121.6TWh in 2030, as shown in Figure 4.5.

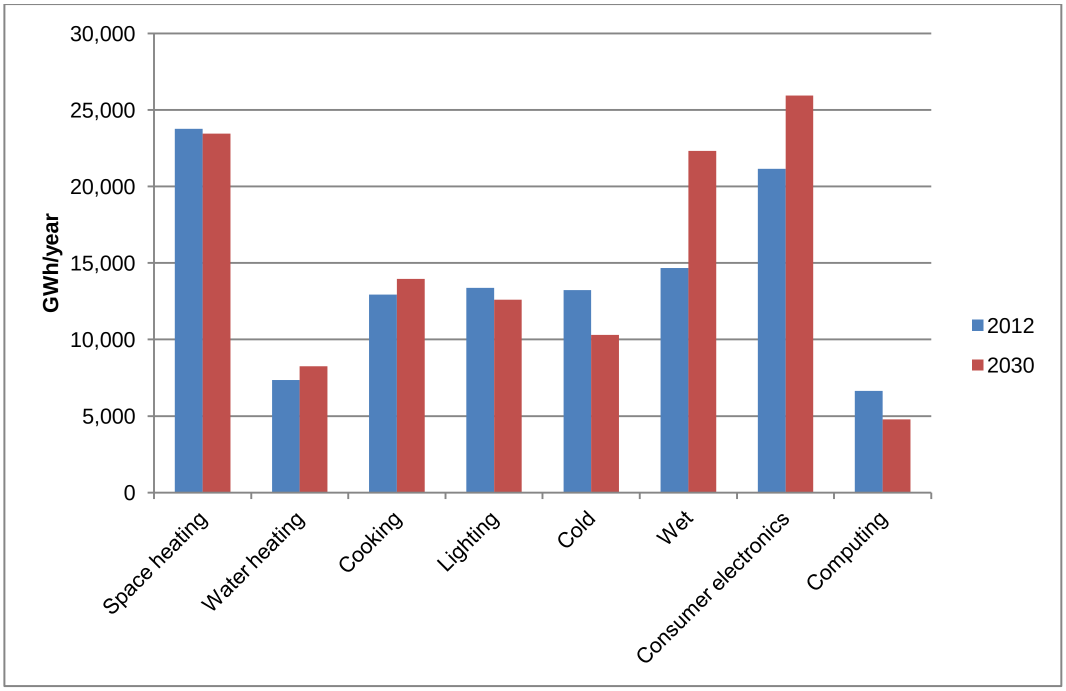


Figure 4.5 GB domestic electricity demand 2012 and 2030

The main increases are found in space heating and water heating (ESWH) and the wet and consumer electronics categories, and the main reductions in the cold, computing and lighting categories.

Trends for individual appliance category consumption vary according to use, household numbers and composition, and technological changes, including improved levels of efficiency. Long term UK trends for each appliance category are shown in Figure 4.6 and the percentage allocation of demand between different categories of lighting and appliance in Figure 4.7. Results from 1970 to 2012 are sourced from ECUK data [13].

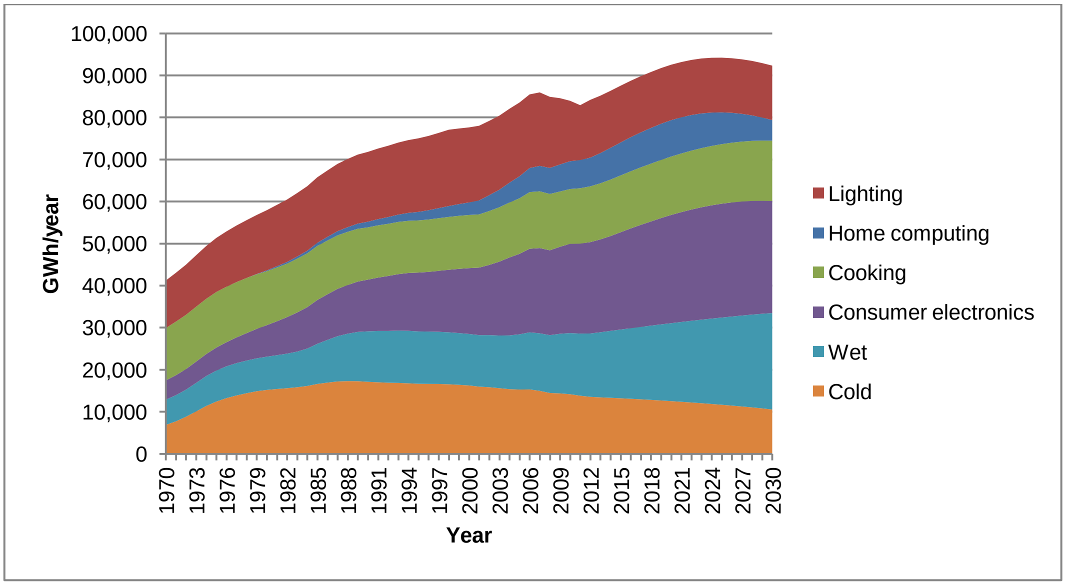


Figure 4.6 UK annual domestic appliance electricity demand 1970 – 2030

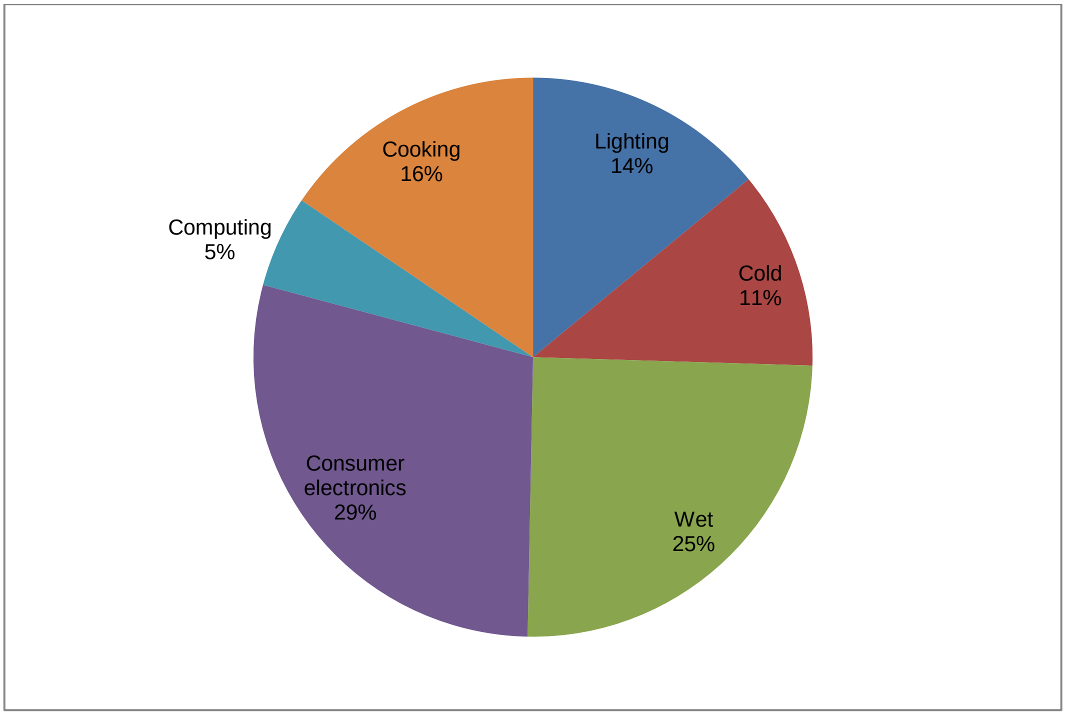


Figure 4.7 UK annual domestic electricity demand - lighting and appliances in 2030

4.3.1 Electric space and water heating (ESWH)

Annual electricity demand for ESWH is projected to increase from 31,114GWh in 2012 to 31,702GWh in 2030. Calculations are based on assumptions from CCC Decarbonising heat report (2010) [21] which indicate a reduction of 8.6% in overall heat demand by 2030, but with a higher proportion of heat from electric power.

Current demand, mainly met through gas, is 401.3TWh pa which reduces to 366.8TWh pa in 2030. The ratio of space heating demand and water heating demand in 2012 is 79.9:20.1 [13]. The CCC “Decarbonising heat: Low-carbon heat scenarios for the 2020’s” report [21] forecasts 28% of space heating being supplied from heat pumps by 2030. This study assumes all electric space heating in 2030, i.e. 82,056GWh, is delivered by heat pumps, which, with a heat pump coefficient of performance (COP) of 3.5, results in 23,445GWh electricity required. This study also assumes that 28% of water heating in 2030, i.e. 20,644GWh, is delivered by heat pumps, which, with a heat pump COP of 2.5 (lower efficiency than space heating due to higher temperature requirements), results in 8,257GWh electricity required. It is recognised that these assumptions result in a conservative total annual ESWH demand as it is probable that not all electric heat will be delivered by heat pumps.

4.3.2 Cold appliances

The 2012 annual electricity consumption for domestic cold appliances in the UK was 13,595GWh, made up of 1,256GWh chest freezers, 7,920GWh fridge freezers, 1,931GWh refrigerators and 2,489GWh upright freezers. Cold appliance electricity demand is projected to decline from 13,595GWh in 2012 to 10,585GWh in 2030, as shown in Figure 4.8.

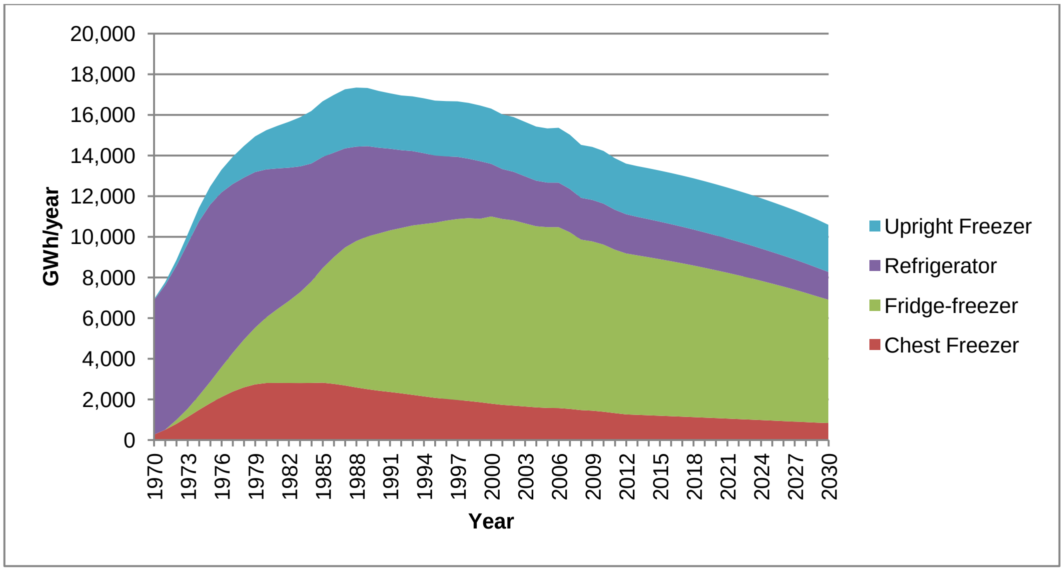


Figure 4.8 UK annual domestic electricity demand by cold appliances 1970 – 2030

Increased efficiency levels offset the increase in numbers of households resulting in an overall decline in demand.

4.3.3 Wet appliances

The 2012 annual electricity consumption by wet appliances in the UK was 15,073GWh, made up of 4,582GWh washing machine, 2,431GWh washer dryer, 3,338GWh dishwasher and 4,722GWh tumble dryer. Wet appliance electricity demand is projected to increase from 15,073GWh in 2012 to 22,938GWh in 2030, as shown in Figure 4.9.

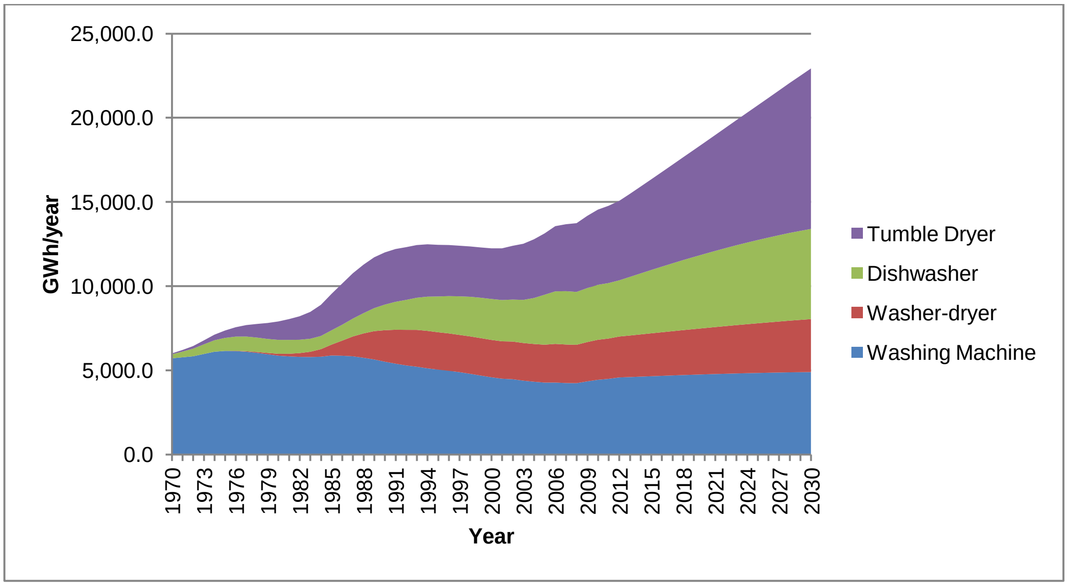


Figure 4.9 UK annual domestic electricity demand by wet appliances 1970 – 2030

The main factors affecting consumption, by sub-category, are improved efficiency reducing the effect of increased ownership levels and household numbers of all appliances, though tumble dryer demand more than doubles (from 4,722GWh to 9,533GWh) reflecting changes in types of households and drying practices.

4.3.4 Lighting

The 2012 annual electricity consumption by domestic lighting in the UK was 13,747GWh, made up of 1,651GWh standard light bulb (SLB), 6,908GWh halogen, 1,221GWh fluorescent strip lighting, 3,861GWh energy saving light bulb (ESB) and 105GWh LED. Lighting electricity demand is projected to decline from 13,747GWh in 2012 to 12,949GWh in 2030, as shown in Figure 4.10.

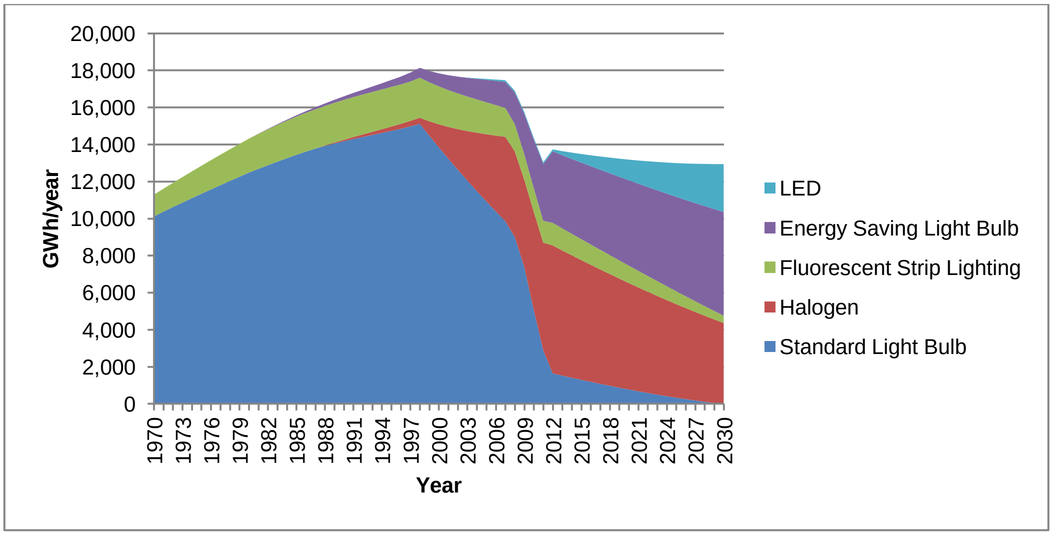


Figure 4.10 UK annual domestic electricity demand by lighting 1970 – 2030

Standard light bulbs are substantially replaced by energy saving light bulbs by 2020 which contributes the main reduction in demand. The recent increase in the use of halogens slows and fluorescent strip lighting continues to decline in usage.

4.3.5 Consumer electronics

The 2012 annual electricity consumption by consumer electronics in the UK was 21,725GWh, made up of 8,676GWh TV, 4,233GWh set top box, 1,803GWh DVD/VCR, 942GWh games console and 6,071GWh power supply. Consumer electronics demand increases from 21,725GWh in 2012 to 26,656GWh in 2030, as shown in Figure 4.11.

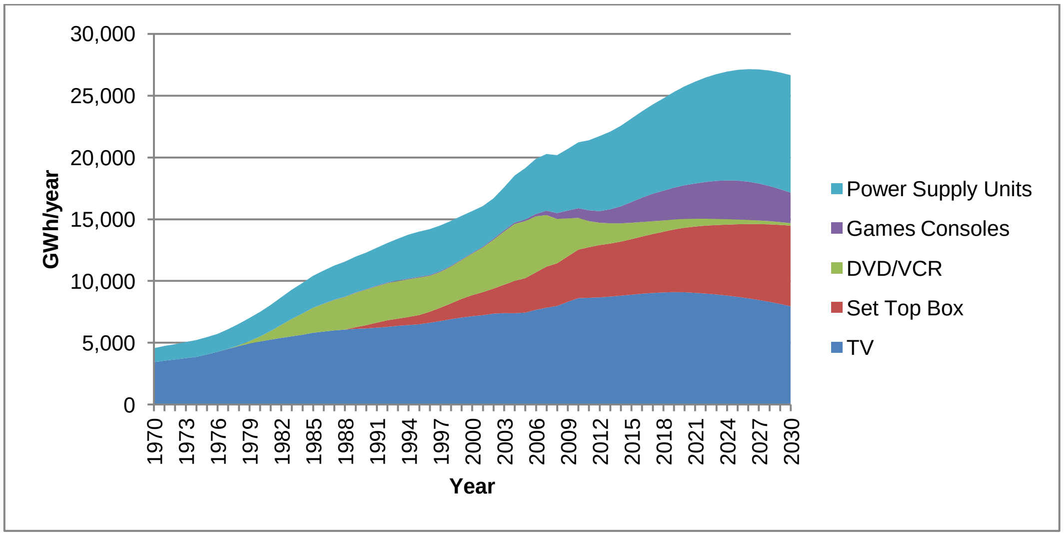


Figure 4.11 UK annual domestic electricity demand by consumer electronic appliances 1970 – 2030

Ownership levels of TVs, set top boxes and games consoles increase whilst the popularity of DVD/VCRs continues to decline as alternative media sources become more widespread. Increased levels of ownership are partially offset by improved levels of appliance efficiency.

4.3.6 Home computing

The 2012 annual electricity consumption by home computing in the UK was 6,827GWh, made up of 3,175GWh desktop, 1,489GWh laptop, 1,768GWh monitor, 116GWh printer and 279GWh multi-function device. Home computing demand declines from 6,827GWh in 2012 to 4,909GWh in 2030, as shown in Figure 4.12.

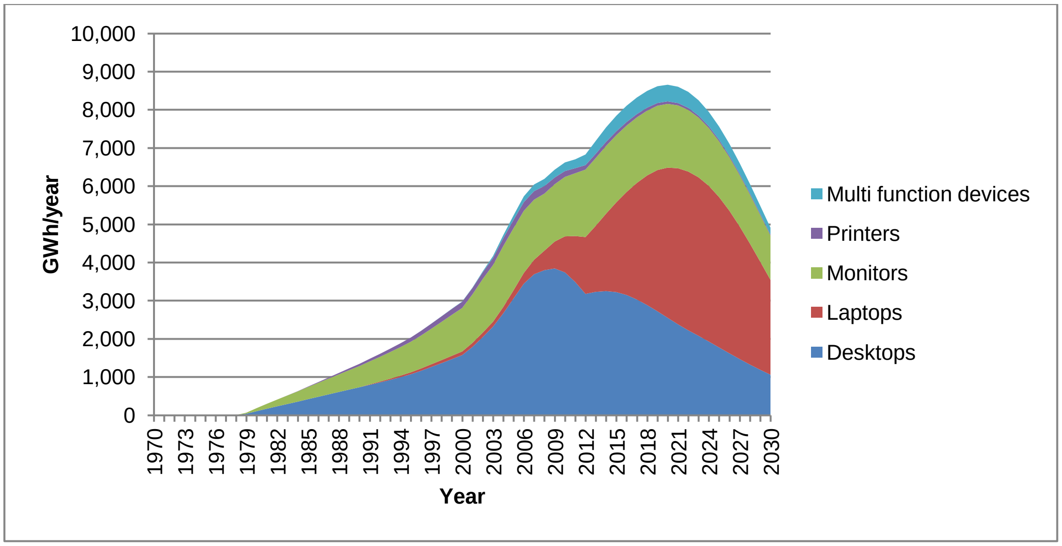


Figure 4.12 UK annual domestic electricity demand by home computing appliances 1970 – 2030

Reductions in energy consumption of desktops and monitors outweigh increases in laptops and multi-function devices.

4.3.7 Cooking

The 2012 annual electricity consumption by cooking appliances in the UK was 13,270GWh, made up of 3,117GWh electric oven, 3,140GWh electric hob, 2,524GWh microwave and 4,489GWh kettle. Cooking demand increases from 13,270GWh in 2012 to 14,337GWh in 2030, as shown in Figure 4.13.

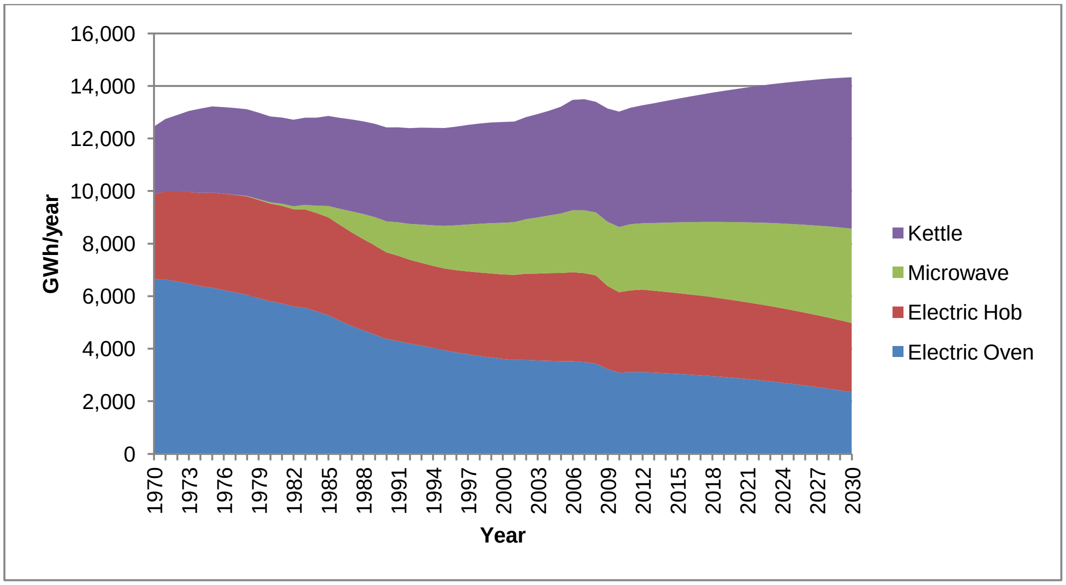


Figure 4.13 UK annual domestic electricity demand by cooking appliances 1970 – 2030

Increases in household numbers and use patterns result in increased demand from microwaves and kettles, whereas improved appliance efficiency and changes in cooking practices result in a decline in demand from electric ovens and hobs.

4.4 Flexible annual domestic electricity demand in 2012 and 2030

The total annual electricity demand by ESWH, cold and wet appliances is projected to increase from 59,024GWh in 2012 to 64,326GWh in 2030, with changes to flexible demand categories shown in Figure 4.14.

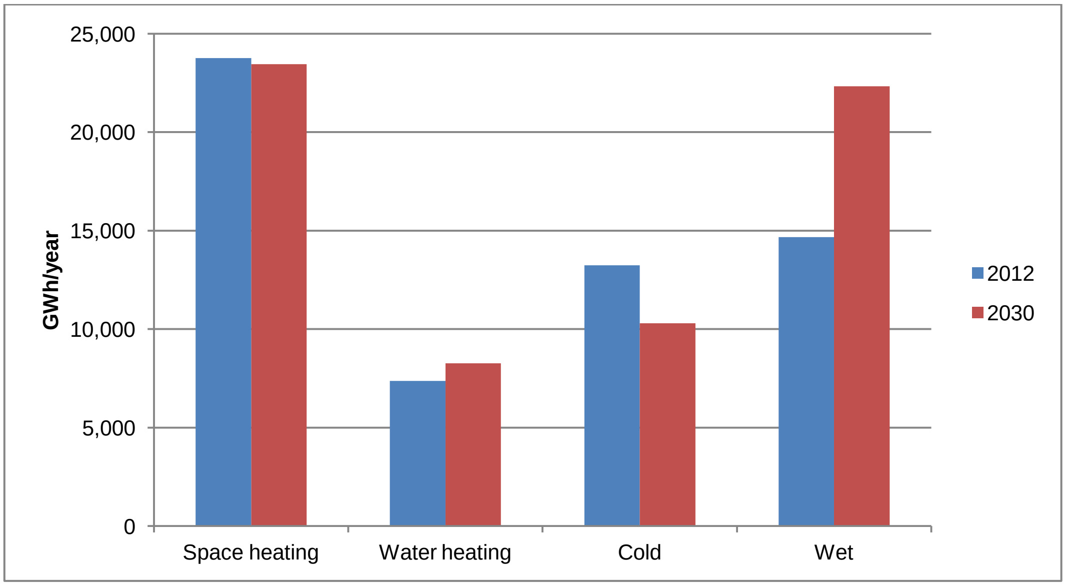


Figure 4.14 Flexible domestic electricity demand in 2012 and 2030

Increases in the amount of electric space heating and water heating (ESWH), due to a greater penetration of heat pumps, and wet appliance demand, due to changes in appliance usage rates, are partially offset by reductions in cold appliance demand due to improved appliance efficiency.

4.5 Flexible domestic electricity category load profiles

Daily load profiles for ESWH, cold appliances and wet appliances are based on profiles from the Household Electricity Survey (HES) [23]. The magnitude of these profiles has been adjusted to reflect the difference between the projected total UK domestic demand in 2030, from this study, and the annual demand from the smaller dataset of the HES, whilst maintaining the same overall profile

4.5.1 Electric space and water heating (ESWH) daily load profile

ESWH demand is highly seasonal with a higher demand in winter, due to lower ambient external temperatures, than in summer, when demand for space heating drops significantly, as shown in Figure 4.15.

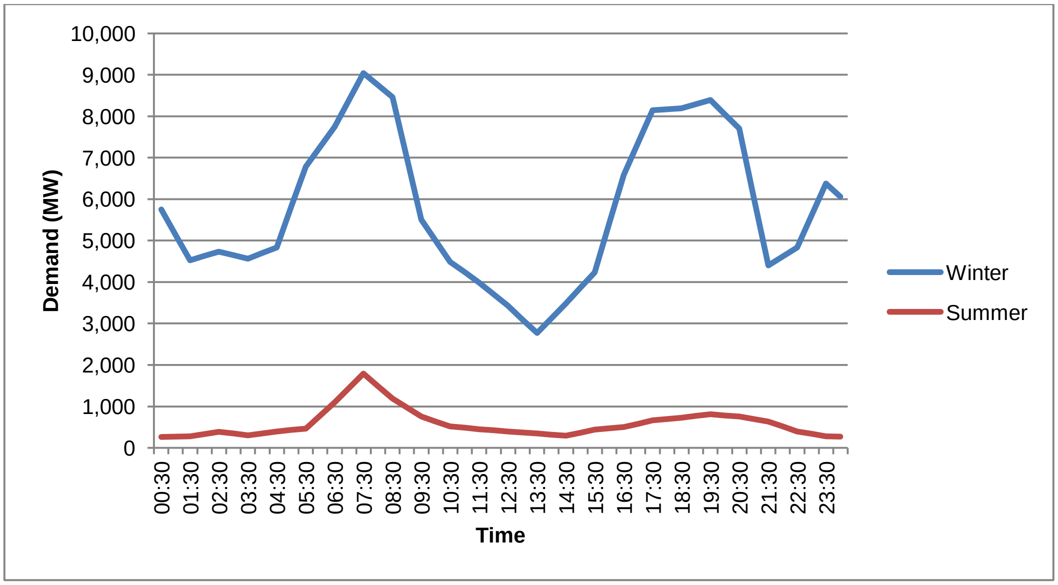


Figure 4.15 ESWH daily load profile in winter and summer 2030

4.5.2 Cold appliances daily load profile

Cold appliance electricity demand is subject to seasonal variations, with summer peak consumption at approximately 1.15 of the annual average and winter low consumption at approximately 0.8 of the annual average, reflecting changes in ambient temperatures [27], as shown in Figure 4.16.

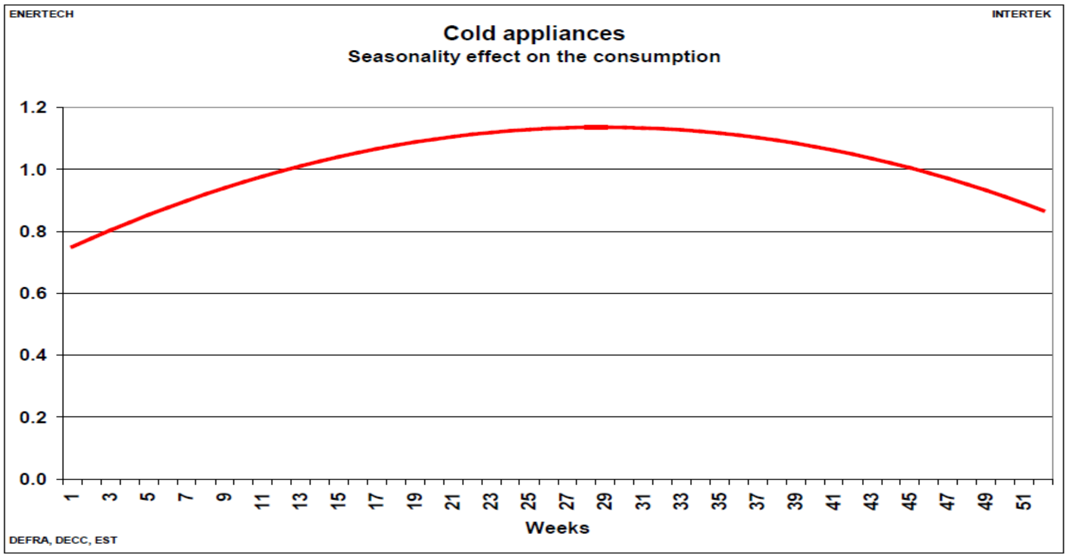


Figure 4.16 Cold Appliances – Seasonality effect [27]

There is also a minor fluctuation in daily loads with consumption slightly above average at times of high household occupancy and usage e.g. at meal times [28], as shown in Figures 4.17 (winter) and 4.18 (summer).

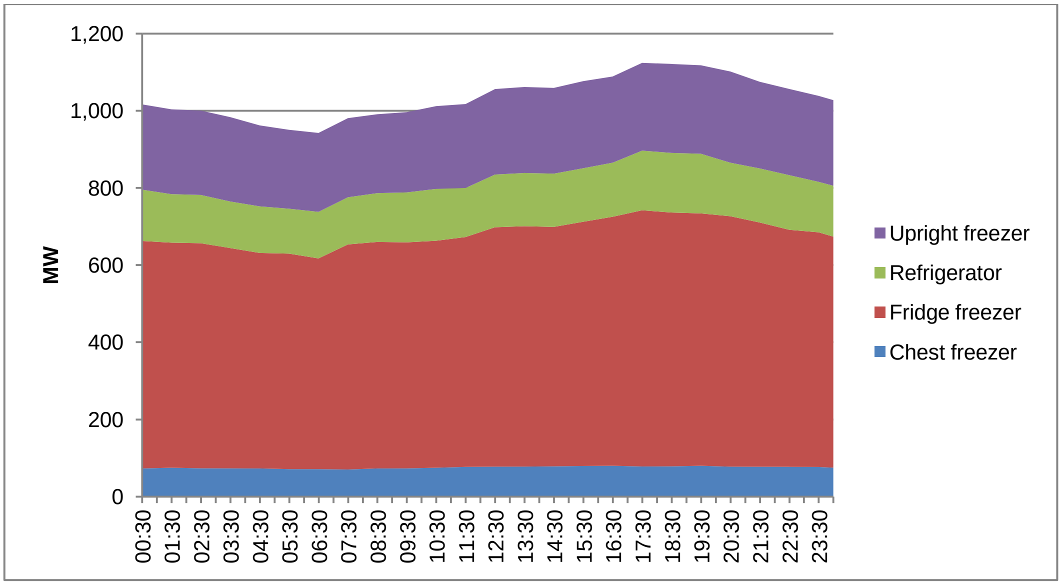


Figure 4.17 Cold appliance daily load profile in winter 2030

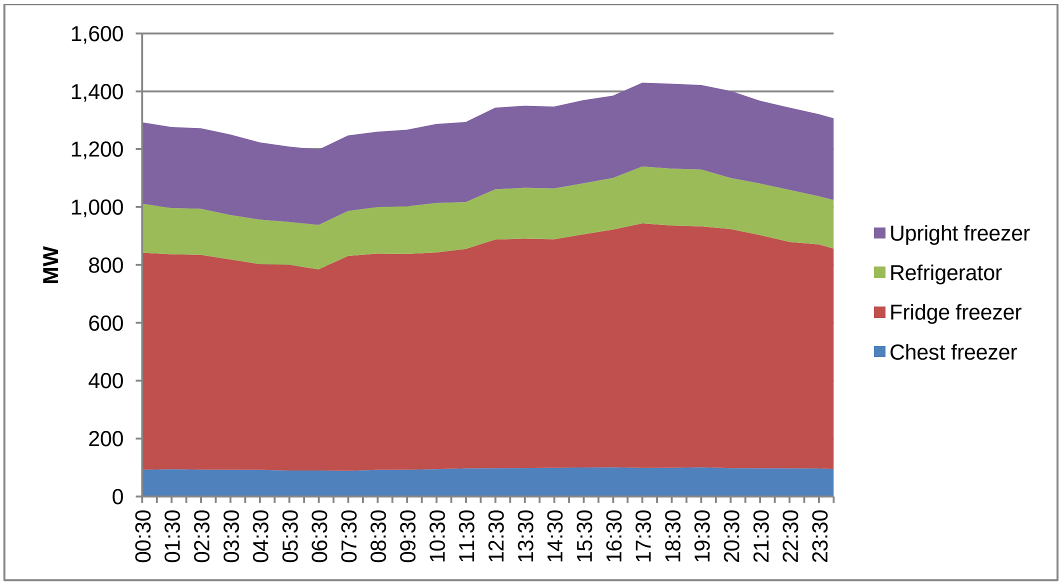


Figure 4.18 Cold appliance daily load profile in summer 2030

4.5.3 Wet appliances daily load profile

Wet appliance electricity demand is subject to seasonal variations, with winter peak consumption at approximately 1.35 of the annual average and summer low consumption at approximately 0.85 of the annual average, reflecting greater heating requirements and requirements to dry clothes with dryers rather than on clothes lines in winter [29], as shown in Figure 4.19.

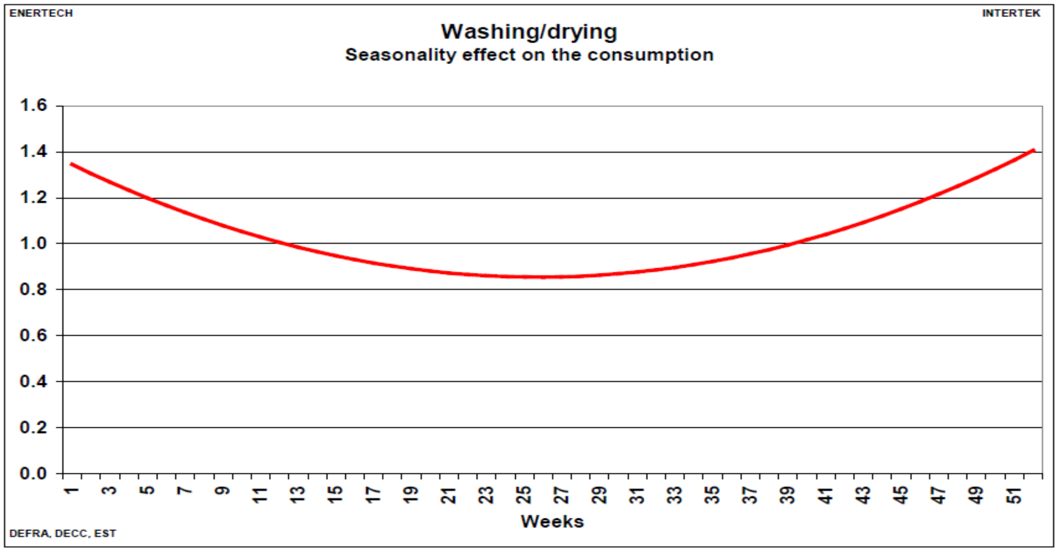


Figure 4.19 Wet Appliances – Seasonality effect [29]

Electricity demand by wet appliances varies significantly throughout an average day and by season, as shown in Figures 4.20 (seasonal variations) and 4.21 (average profile by appliance type).

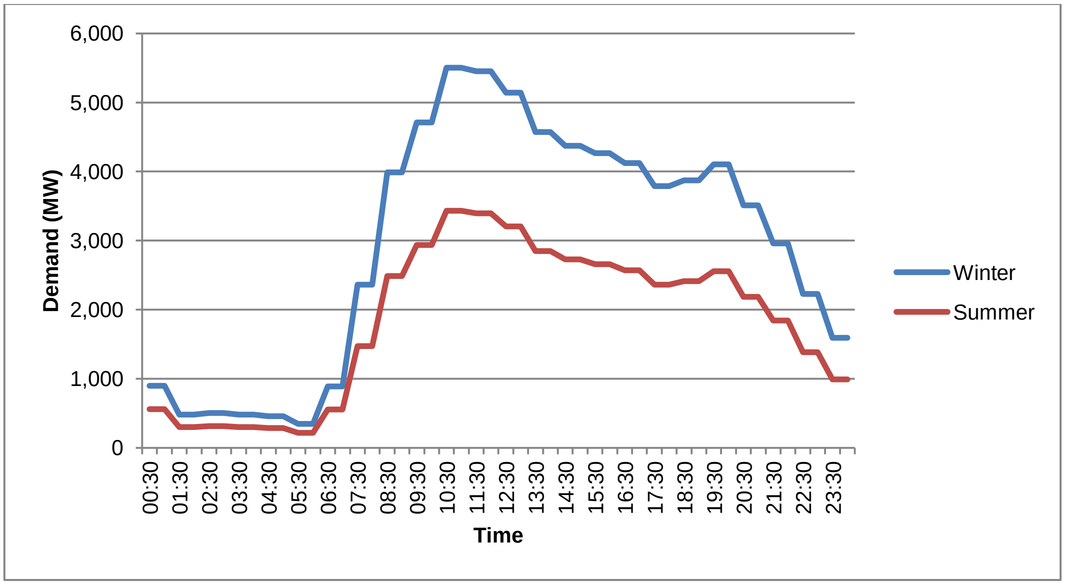


Figure 4.20 Wet appliance daily load profile in winter and summer 2030

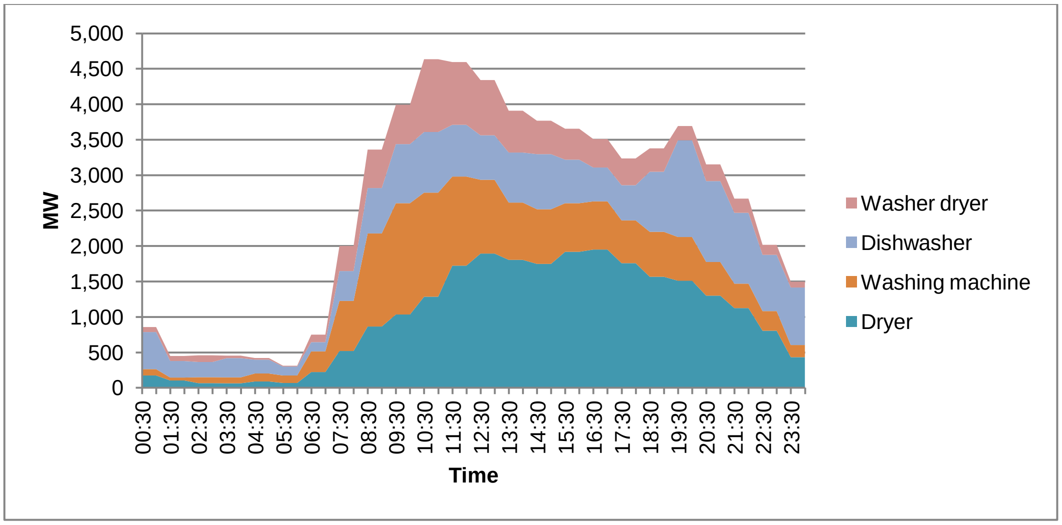


Figure 4.21 Wet appliances average daily load profile in 2030

4.5.3.1 Washing machine daily load profile

The washing machine load profile for 2030, detailed on Figure 4.22, shows a mid morning peak of 1,451MW at 09:30, reflecting a usage pattern where washing machines are activated after breakfast. Demand drops after this initial peak and reaches a plateau of approx 600MW at 13:00 until 20:00. Demand drops after 20:00 and remains at a low level overnight. The lowest level of demand is 38MW at 01:30.

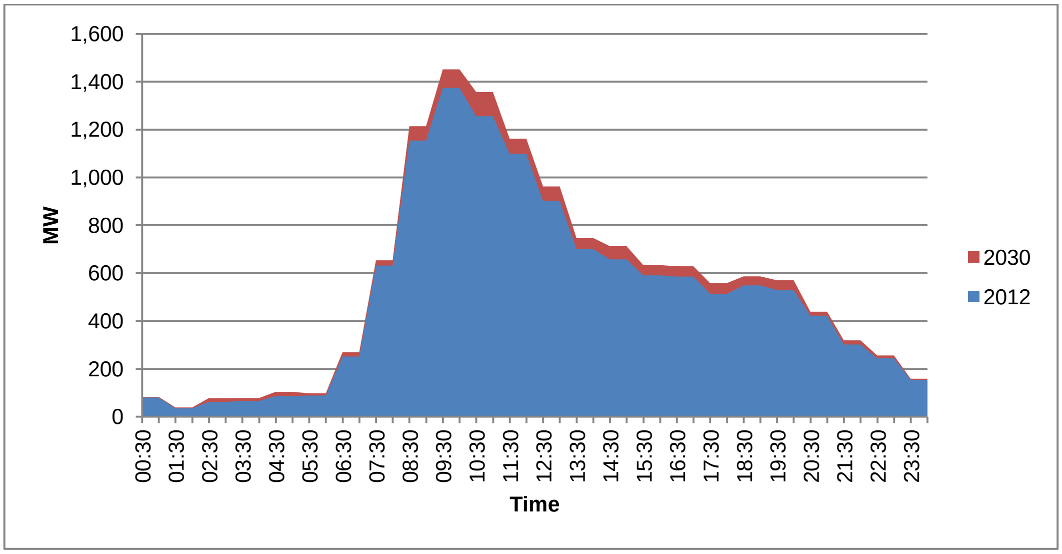


Figure 4.22 Washing machine average daily load profile in 2012 and 2030

4.5.3.2 Dryer daily load profile

The dryer load profile for 2030,detailed on Figure 4.23, shows peak demand at 13:00 (1,614MW) and 16:30 (1,662MW) reflecting a link to the washing machine profile. Dryers are used immediately after the morning washing machine cycle has completed, and later in the afternoon when occupants return home. The lowest level of demand is 53MW at 03:30.

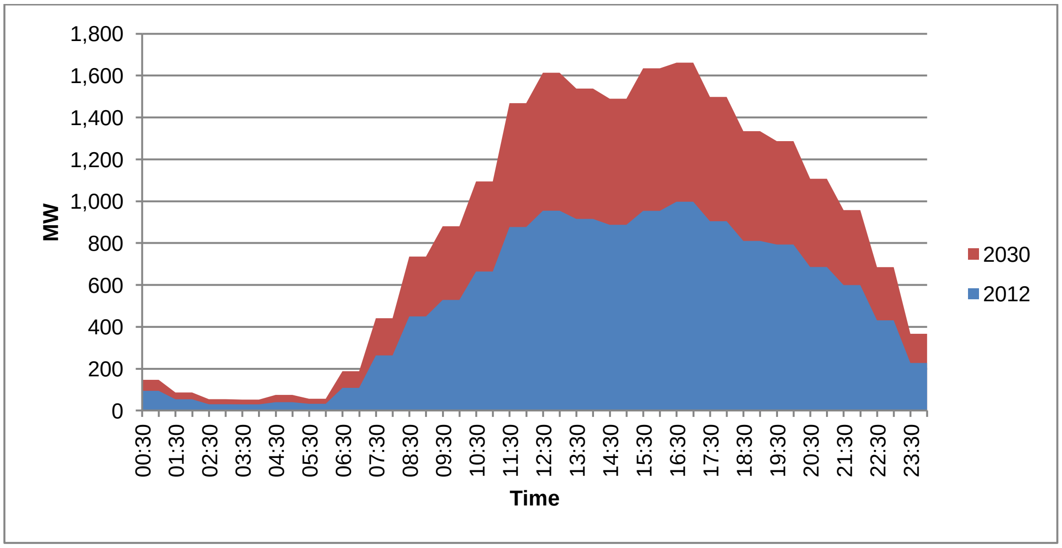


Figure 4.23 Dryer average daily load profile in 2012 and 2030

4.5.3.3 Washer dryer daily load profile

The washer dryer load profile for 2030, detailed on Figure 4.24, shows an increase in demand from 06:30 to 08:00 when it remains at approx 500MW. Demand then increases to a peak of 954MW at 10:30 reflecting increased usage and operation of the dryer cycle. Overnight demand is low and the lowest level of demand is 11MW at 05:30.

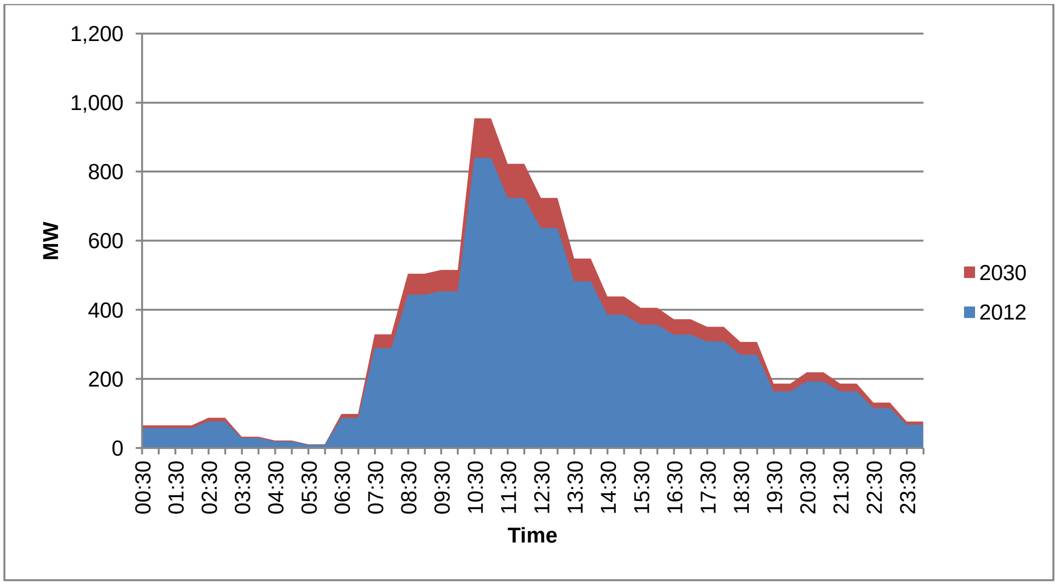


Figure 4.24 Washer dryer average daily load profile in 2012 and 2030

4.5.3.4 Dishwasher daily load profile

The dishwasher load profile for 2030, detailed on Figure 4.25, shows increased usage following the traditional mealtimes at breakfast (583MW at 10:30), mid-day (529MW at 14:30) and early evening (929MW at 19:30). The lowest level of demand is 86MW at 05:30.

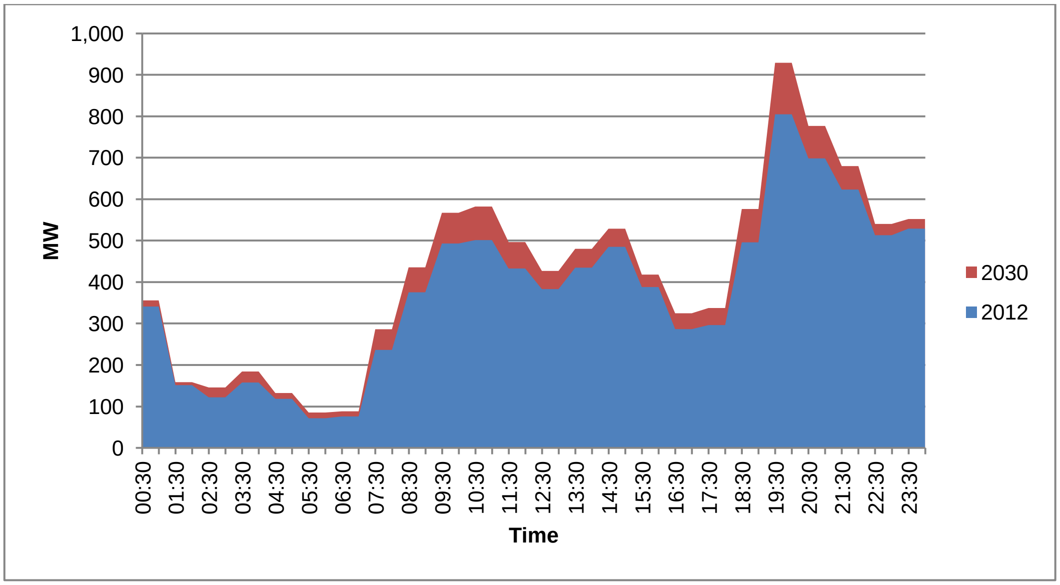


Figure 4.25 Dishwasher average daily demand profile in 2012 and 2030

The profiles highlight the links between appliance usage and other activities e.g. dishwasher use following mealtimes, dryer use following washing machine usage and household occupancy, and washing machines and washer dryers being activated after breakfast. It is also clear that wet appliance use is lowest between 00:00 and 07:30 reflecting the sleep patterns of household occupants. This may be because occupants are not present to initiate wet appliance operations or because there is a reluctance to have noisy appliances running during the night with the potential to cause a disturbance.

4.6 Potential flexible domestic electricity demand in 2030

The amount of flexible domestic demand in GB is projected in this study to increase from 59.0TWh in 2012 to 64.3TWh in 2030, though the amount varies significantly on a diurnal, weekly and seasonal basis. Additionally, the amount of practically available flexible domestic demand is less than the maximum flexible demand and is dependent on permissions being granted to access load, duration of access [30] and how recent previous interventions have been made.

4.6.1 Maximum flexible domestic electricity demand in 2030

The 2030 combination of ESWH and cold and wet appliances load profiles by season, is shown in Figure 4.26, and by appliance type in Figure 4.27 (winter) and Figure 4.28 (summer).

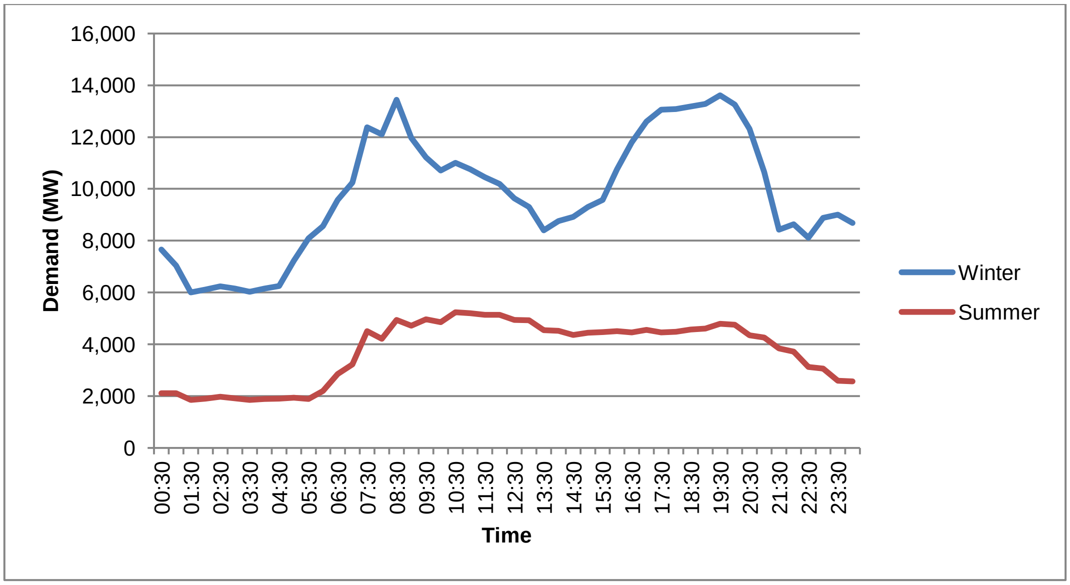


Figure 4.26 Flexible domestic daily load profile in winter and summer 2030 (maximum)

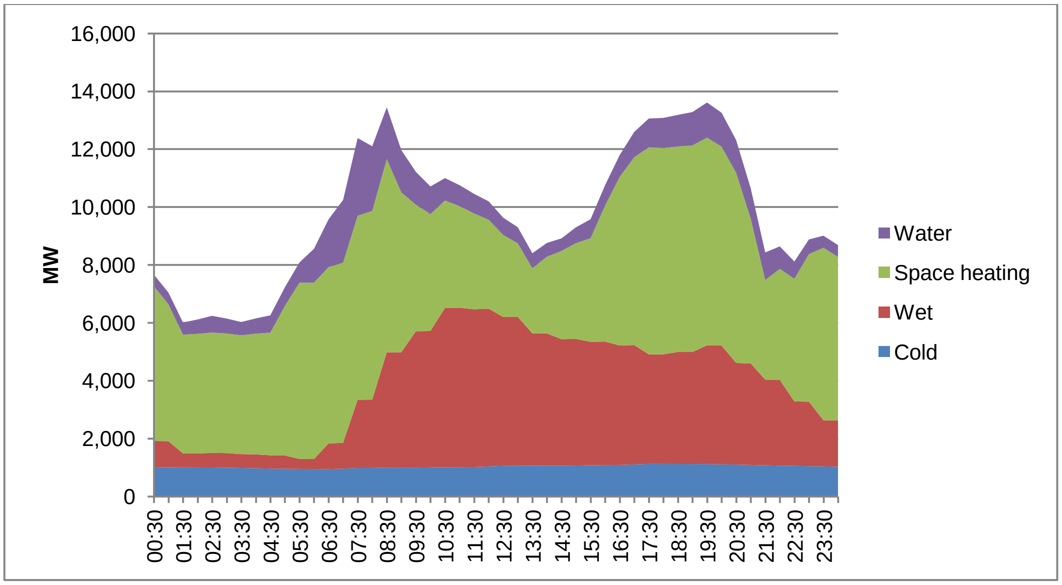


Figure 4.27 Maximum flexible domestic daily load profile in winter 2030

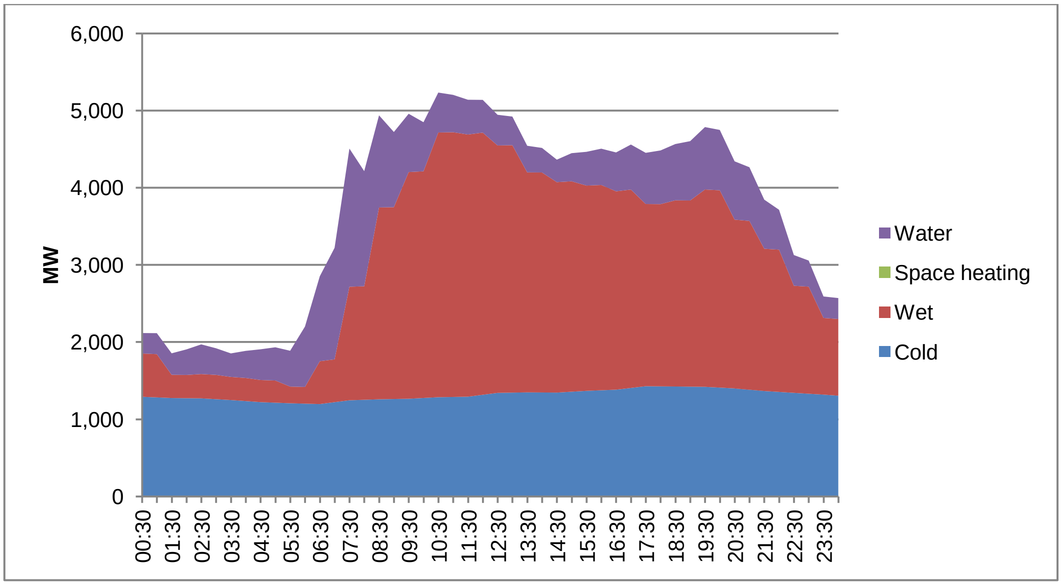


Figure 4.28 Maximum flexible domestic daily load profile in summer 2030

The maximum available flexible domestic demand in 2030, available at different time points during two sample days (winter and summer), are shown with the 2012 total GB system demand on the same days, in Tables 4.2 and 4.3.

Table 4.2 Maximum flexible domestic demand in 2030 (winter)

Winter (time)	System demand (MW) (21/12/12)	Theoretical maximum FDD (MW) (2030)	Cold (MW)	Wet (MW)	Space heating (MW)	Water heating (MW)
05:00	31,292	7,228	956	461	5,165	646
08:00	43,214	12,100	986	2,361	6,516	2,237
17:30	49,936	13,058	1,124	3,788	7,152	994

Table 4.3 Maximum flexible domestic demand in 2030 (summer)

Summer (time)	System demand (MW) (21/06/12)	Theoretical maximum FDD (MW) (2030)	Cold (MW)	Wet (MW)	Space heating (MW)	Water heating (MW)
05:00	25,202	1,935	1,217	287	0	431
08:00	37,507	4,217	1,254	1,471	0	1,492
17:30	41,299	4,454	1,430	2,361	0	663

4.6.2 Practically available flexible domestic electricity demand in 2030

The amount of flexible domestic demand available is dependent on access being granted by domestic consumers. A study of public values, attitudes and acceptability to changes within the UK energy system [31] has found varying levels of acceptability of allowing load flexibility for different appliances. The survey of 2,441 respondents, found acceptance levels of 58% for washing machines, 40% for fridges and 43% for heating. When these percentages are applied to the maximum load profiles the reduced amount of flexible demand which is practically available is significantly lower, as shown in Figure 4.29.

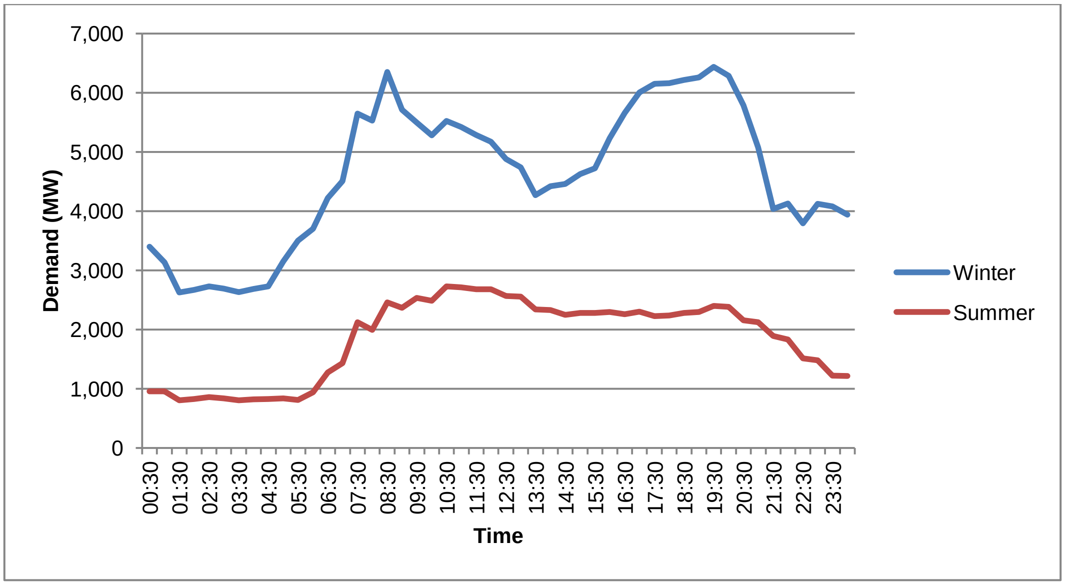


Figure 4.29 Flexible domestic daily load profile in winter and summer 2030 (practically available)

The practically available flexible domestic demand in 2030, available at different time points during two sample days (winter and summer), are shown with the 2012 total GB system demand on the same days, in Tables 4.4 and 4.5.

Table 4.4 Practically available flexible domestic demand in 2030 (winter)

Winter (time)	System demand (MW) (21/12/12)	Practical FDD (MW) (2030)	Cold (MW)	Wet (MW)	Space heating (MW)	Water heating (MW)
05:00	31,292	3,148	382	267	2,211	278
08:00	43,214	5,527	394	1,369	2,802	962
17:30	49,936	6,150	449	2,197	3,075	428

Table 4.5 Practically available flexible domestic demand in 2030 (summer)

Summer (time)	System demand (MW) (21/06/12)	Practical FDD (MW) (2030)	Cold (MW)	Wet (MW)	Space heating (MW)	Water heating (MW)
05:00	25,202	838	487	166	0	185
08:00	37,507	1,996	502	853	0	641
17:30	41,299	2,226	572	1,369	0	285

Chapter 5

Consumer engagement and access to flexible domestic demand

Summary:

This chapter uses data from the quantitative survey and qualitative workshops of the UKERC funded project “Transforming the UK Energy System: Public Values, Attitudes and Acceptability”. *The dataset analysis is the work of the author/researcher.*

The chapter considers three questions relating to access to flexible domestic electricity demand:-

- *What relationship do consumers have with their electricity consumption?*
- *How acceptable is appliance automation to domestic consumers?*
- *What incentives would encourage domestic consumers to engage more with their electricity consumption and allow access to flexible domestic demand?*

5.1 Introduction

5.1.1 Research questions

This chapter considers three research questions relating to access to flexible domestic electricity demand, namely:-

What relationship do domestic consumers have with their electricity consumption?

How acceptable is appliance automation to domestic consumers?

What incentives would encourage domestic consumers to engage more with their electricity consumption and allow access to flexible domestic demand?

Effective demand side management (DSM) requires demand to vary in response to an external signal. This can be done automatically, through appliance automation, or manually by household occupants modifying their consumption behaviour in a way which supports the effective and efficient operation of the electricity system. The relationship consumers have with their electricity consumption impacts on their ability to play an active role in DSM. The more engaged consumers are the more able they are to make conscious decisions about their consumption in a dynamic timeframe. The less engaged they are the greater the requirement for appliance automation to deliver demand flexibility.

Appliance automation can help deliver the necessary flexibility in electricity consumption, required for effective DSM, where domestic consumers are unwilling, or unable, to modify their consumption behaviour in response to an external signal. This would be particularly relevant for conditions requiring a fast response such as frequency control, in a future electricity balancing market. The adoption of appliance automation to support domestic DSM, would be enhanced by technological developments such as the introduction of smart electricity meters to allow timely communication between individual appliances and the requirement of the wider electricity system. It would also require the permission of individual domestic consumers to allow this access.

The participation of domestic consumers in DSM, either in an active way, through unique alterations to consumption, or in a more passive way, by permitting appliance automation, will require some form of incentive, even if that is just by being informed of the societal benefits of engagement. An understanding of the effectiveness of different types of incentive is useful for those interested in developing effective domestic DSM.

5.1.2 Consumer engagement

There are a number of different definitions of consumer engagement [e.g. 1, 2, 3, 4 & 5] ranging from being a mechanism to improve competition in the electricity market, evidenced by the frequency of switching electricity supplier [1], to a wider definition which "*includes attitudes, understanding, meanings, behaviour and practices at individual, community and cultural levels, and also refers to discrete engagement interventions*" [5].

The definition used in this study is "*the extent to which electricity consumers are conscious of their dynamic electricity consumption at an individual appliance use level*" and relates to the "*active consumer*" and "*active demand*" descriptors found in other literature [e.g. 6 & 7].

5.1.3 Barriers to engagement

Lorenzoni et al [8] have identified a number of perceived barriers to engagement in the context of climate change which are also relevant to engagement with electricity consumption. These have been described under individual and social levels, as shown on Table 5.1.

Table 5.1 Barriers to consumer engagement [8]

Individual	Lack of knowledge Uncertainty and scepticism Distrust in information sources Externalising responsibility and blame Technology will save us Climate change is a distant threat Other things are more important Reluctance to change lifestyles Fatalism “Drop in the ocean” feeling
Social	Lack of political action Lack of action by business and industry Worry about free-rider effect Social norms and expectations Lack of enabling initiatives

5.1.4 Access to flexible domestic demand

Flexible domestic demand can deliver benefits across the electricity sector including improving reliability of delivery through more efficient grids, lower energy bills through reducing the need for investment in infrastructure assets, greater integration of intermittent renewable generators and increased energy security [3].

These objectives can be met through efficiency and conservation measures, load shifting, and frequency response [7], with access to each calling for varying levels of engagement, as shown on Table 5.2.

Table 5.2 Extent of engagement required for demand side activity

Activity	**Extent of engagement required**	**Description**
Efficiency	Low	Initial investment e.g. in high efficiency appliances, light bulbs, insulation etc., with minimal change in future consumption patterns or experience.
Conservation	Medium	Requires conscious effort e.g. in reducing thermostat settings, switching off appliances and lighting when not in use.
Load shifting	Medium	Movement of flexible loads e.g. washing machines, dishwashers etc., from periods of high demand (peak) to periods of lower demand (or from periods of low renewable generation to periods of high generation). Can involve direct user control or automation.
Frequency response	High	Requires near instantaneous response which is unlikely to be achieved through direct user control. Appliance automation the most likely access route.

5.1.5 Behaviour and behaviour change

The extent to which consumers can be encouraged to engage with their electricity consumption, and permit access to flexible domestic load, depends on the extent to which consumers are prepared to change their consumption behaviour. Behaviour and behaviour change theories range from economic, rational choice theories to wider social theories involving practices determined by societal norms and structures [9]. Different academic disciplines address behaviour in different ways, as summarized in Table 5.3.

Table 5.3 Academic disciplines approach to behaviour theory

Discipline	**Approach**
Economics	- rational choice model - neoclassical - utility maximization acting on available information - conscious decisions
Psychology	- individual actors initiating behaviour - ABC – Attitude, Behaviour, Choice/Context - information provision
Sociology	- social level of practice which drives individual actions
Engineering	- behaviour in relation to technology
Policy	- behaviour as observable action - “policy based evidence” or “evidence based policy” - “heavy” theory not used - Nudge

5.2 Behaviour and behaviour change theory

There is an extensive literature in the social sciences regarding behaviour and behaviour change theories and models. These range from behaviour as an outcome of rational choice by an individual (rational choice theory) to society wide norms and structures which dictate everyday practices outwith the conscious control of the individual. Reviews of the literature have been addressed to the academic community [e.g.5 & 10] and to the political and policy making community [e.g.11, 12, 13 & 14] and include research specific to energy consumption.

The following section briefly identifies some of the key theories and models relating to energy consumption behaviours.

5.2.1 General principles of behaviour theory

An understanding of why people behave in certain ways has been sought for many centuries, at least since the time the Greek philosophers applied scientific thought to reason and logic in the 6th century BC. In more recent times, from the renaissance and industrial revolution onwards, the dominant model has been one of rational behaviour being defined in terms of economic rationality i.e. behaviour driven by a desire for the maximisation of materialistic objectives such as profit for producers and utility for consumers [15].

Adam Smith, in his 1776 essay “Wealth of Nations”, was one of the early exponents of self-interest as a fundamental driver of behaviour in the context of explaining economic market models. Edgeworth, in his 1881 essay “Mathematical Psychics” [16], stated that “the first principle of Economics is that every agent is actuated only by self-interest” and this economic theory that the “assumption of utility maximisation and equilibrium in the behaviour of groups (became) the traditional foundations of rational choice analysis and the economic approach to behaviour” [17].

The limitations of this approach are clear, and that, whilst utility maximization and equilibrium may be helpful in the explanation of economic behaviour, they are not necessarily appropriate as an explanation of social behaviour [15]. To broaden explanations of human behaviour, the definition of man acting in purely rational economic terms (homo economicus) was joined by other behavioural categories explaining economic non-rationality or non-economic rationality (homo sociologicus) [15].

This latter category included behavioural definitions of homo religiousus, homo moralis, homo habitus, homo eroticus, homo politicus, homo honorus and homo instituted [18], and concludes that homo economicus + homo sociologicus = homo complexicus [15].

There are many other theories seeking to explain rational behaviour though, for the purposes of this chapter, a summary from [15] is useful:-

- rational behaviour can be economic or individual, and extra-economic or social

- the extension of a neoclassical viewpoint of rational behaviour into other fields is flawed
- rational behaviour exhibits both economic and non-economic rationality, and human behaviour can be economically non-rational and rational in non-economic terms”

The different displays of rational behaviour are shown on Table 5.4 below [15].

Table 5.4 Modes of Rational Behaviour and the Type of Teleology (Purpose) [15]

Modes of Rational Behaviour	**Type of Teleology**
Economic instrumental rational behaviour (instrumentally-rational action)	Materialistic purposes: utility, profit or money and other economic maximands
Non-economic/non instrumental (value-rational action)	Idealist purposes: power, prestige, moral duties, religious values, justice, and other non-economic considerations
Objective, universal rational behaviour	Real or imputed purposes by the analyst or alter
Subjective, local rational behaviour	Good reasons from the agent’s standpoint
Perfect, unlimited rational behaviour	Maximization of purposes, material or ideal
Imperfect, bounded rational behaviour	All-or-none realization of purposes, or satisficing
Formal-procedural rational behaviour or accounting	Quantitative or calculative purposes e.g. profit
Substantive rational behaviour	Qualitative or transcendental purposes and ultimate values
Authoritative, single-exit rational behaviour	Forced upon actors by someone else viz the imperative of utility optimizing or revolutionary praxis or system survival decreed or recommended by the analyst
Liberal, multiple-exit rational behaviour	The outcome of the agent’s free choice among alternative purposes, e.g. economic and non-economic
Institutional, constitutional, constrained rational behaviour	Purposes of agents living in society as a structural constraint on individual actions
Monad type, Hobbesian rational behaviour: unrestrained egotism or universal war	Robinson Crusoe’s purposes in an asocial state of nature

The distinctions are important as, when forming policies dependant on human behavioural responses, an understanding of what kind of response can be expected i.e. what kind of responses are rational, in different contexts, depends on a wide range of factors which need to be considered.

There are a number of models explaining theories of behaviour, including Ajden's theory of planned behaviour, Triandis' theory of interpersonal behaviour, Argyris & Schon's double loop learning and Gibbons & Gerrard's prototype/willingness model.

Diagrams of Ajden's and Triandis' theories are shown on Figures 5.1 and 5.2:-

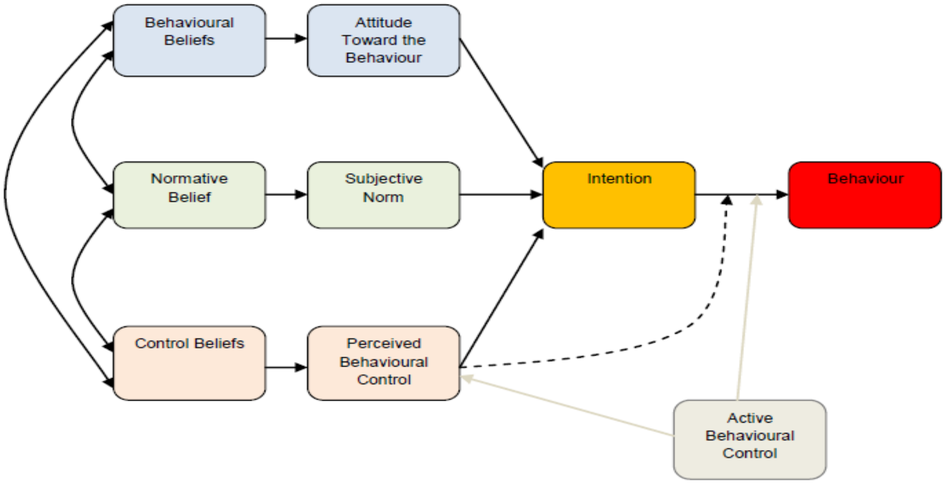


Figure 5.1 Ajden's Theory of Planned Behaviour [19]

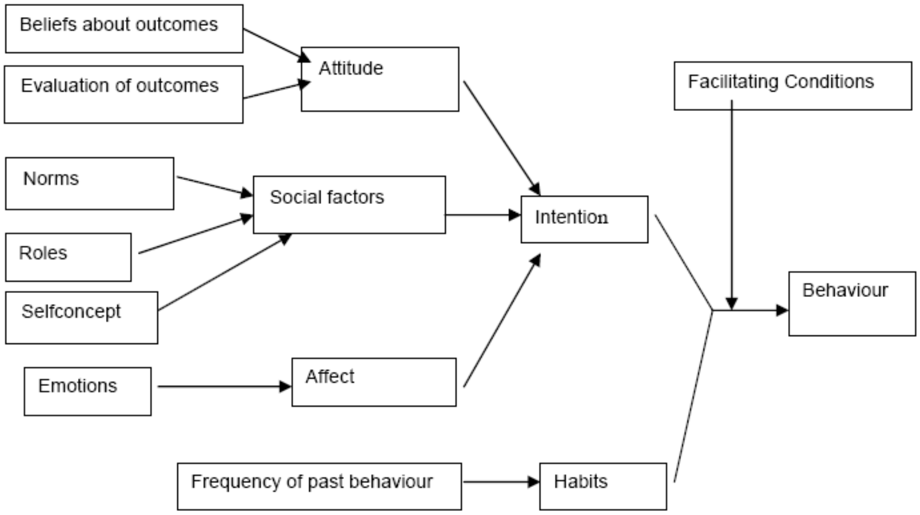


Figure 5.2 Triandis' Theory of Interpersonal Behaviour [20]

5.2.2 The role of feedback

Energy use is largely invisible to consumers leading to a lack of connection between behaviour and energy efficiency.

Common themes from studies carried out during the 1970’s are that feedback via display units is effective at influencing consumer behaviour and, therefore, worth pursuing, and feedback can be used as a learning tool to allow users to teach themselves. More recent studies also see feedback as a mechanism to increase tacit knowledge of energy use by consumers [21].

Different forms of feedback, such as direct, indirect, inadvertent, utility controlled and energy audits have shown to contribute towards savings in energy use of up to 15% [21] though these are difficult to assess accurately due to the different contexts of the studies [22], and other surveys have suggested 0.5 – 1% savings under different levels of feedback [23].

Other issues include the difficulty in identifying which particular piece of equipment is using energy – “consider groceries in a hypothetical store totally without price markings, billed via a monthly statement… How could grocery shoppers economise under such a billing regime” [24].

Studies in Norway during the 1990’s [25] and [26] have indicated that feedback leads to persistent changes in consumer behaviour. Other studies [27] and [28] have shown there is a greater acceptance of feedback when energy use is compared with previous periods than when compared with a comparison group. This is contrary to the effectiveness of using social norms and social marketing with injunctive norms described below [29].

5.2.3 Implications of the rebound effect

It is widely observed that when successful action is taken to reduce energy use through one intervention, the overall energy saving falls short of that anticipated and, in some instances, overall energy use actually increases, a term classed as “backfire” [30]. This phenomenon is variously described as the rebound effect [30], take-back [31] and the boomerang effect [29].

Reasons for this include the theory that improvements in energy efficiency encourage greater use of that particular facility (direct effect). It can also create an indirect effect whereby savings on one energy consuming activity are used on other activities, which may have an even larger impact.

Studies have shown that after insulation has been installed, more of a house is heated and to a higher temperature due to enhanced functional capacity and greater affordability [31]. Greater affluence leading to larger houses, more energy consuming appliances, more leisure time, higher average internal temperatures, more sedentary and less active lifestyles, and higher expectations of comfort are other factors which can reduce anticipated savings in total energy use.

The impact of social marketing, where social norms are used as a mechanism to encourage less energy consuming activities, can have the negative impact of encouraging lower consuming actors to increase their consumption towards the norm. Whilst higher consuming actors may reduce their consumption, the overall effect could be an increase in total consumption [29].

It can be difficult to measure the extent of shortfall associated with the phenomenon though studies have indicated a range of between 10% [30] to 50% [31] against predicted savings.

The unverified “Khazzoom-Brookes (K-B) postulate” states that overall energy consumption will increase if the unit cost of energy does not change following an efficiency improving change [30].

5.2.4 Social norms and social marketing

Research has established that “social norms not only spur but also guide action in direct and meaningful ways” [29].

The way in which social norms are used to promote pro-environmental behaviour, needs to be carefully considered to avoid unintended consequences.

A study carried out in 2007 in California [29] showed that where descriptive norms were used in social norms marketing, to monitor the impact on energy use in 290 households, those who consumed less energy than the norm increased their consumption at broadly the same level as the reduction by those who consumed above the norm.

Where injunctive norms were also incorporated in the marketing, in the form of statements of approval for low consumption and disapproval for higher consumption, consumption for higher than norm participants reduced whilst those lower than norm increased consumption only marginally.

5.2.5 Implications for policymakers

There is growing awareness amongst policymakers of the complexity attached to influencing behaviour in pursuit of policy goals.

In the past, Government campaigns to raise awareness and educate about energy saving initiatives, have been based on the rationalist information deficit model [32], and assumes people will link policy and action, and modify their behaviour accordingly. This model has been widely criticised and, following a number of unsuccessful large scale public awareness campaigns, there is now an acceptance that attitudes are influenced by a wide range of factors which change over time, and within different communities and sub-communities, depending on social, political, cultural and economic factors.

The UK Government has instituted a number of studies to explore the best ways to influence behaviour, leading to reports such as “A framework for pro-environmental behaviours” issued by Defra in January 2008 [33], “Mindspace; Influencing behaviour through public policy” issued by the Institute for Government and the Cabinet Office in March 2010 [34] and “Behaviour Change and Energy Use” issued by the Behavioural Insights Team (the “nudge unit”) at the Cabinet Office in July 2011 [35]. These moves put behavioural theory at the heart of Government policy-making with a renewed understanding of the central role influencing behaviour has on public policy.

“Whether reluctantly or enthusiastically, today’s policymakers are in the business of influencing behaviour, and therefore need to understand the various effects on behaviour their policies may be having. MINDSPACE helps them do so, and therefore has the potential to achieve better outcomes for individuals and society.”
(source: MINDSPACE main report) [34]

The Mindspace report recognises the need to move beyond the traditional method of seeking to change minds (relying on rational choices driven by the provision of incentives and information) to changing contexts (accepting policy needs to be built around inbuilt responses to our environment).

The main influences on behaviour identified by the report’s authors are captured in the mnemonic MINDSPACE, as shown on Table 5.5:-

Table 5.5 MINDSPACE (source: Institute for Government) [34]

Messenger	We are heavily influenced by who communicates information
Incentives	Our responses to incentives are shaped by predictable mental shortcuts such as strongly avoiding losses
Norms	We are strongly influenced by what others do
Defaults	We “go with the flow” of pre-set options
Salience	Our attention is drawn to what is novel and seems relevant to us
Priming	Our acts are often influenced by sub-conscious cues
Affect	Our emotional associations can powerfully shape our actions
Commitments	We seek to be consistent with our public promises, and reciprocate acts
Ego	We act in ways that make us feel better about ourselves

The application of these principles in practical policy setting is set out on Figure 5.3 [34].

Figure 5.3 Mindspace 6 E’s framework for applying mindspace (source: Institute for Government)[34]

Defra's approach includes recognition that there are many different communities and contexts operating within the UK, each with potentially different levels of receptivity to attempts to influence behaviour. Their behaviours unit has established a theory of segmentation, placing the population into seven different categories, allowing a more refined approach to exerting influence through social marketing. This is shown on Figure 5.4 [33].

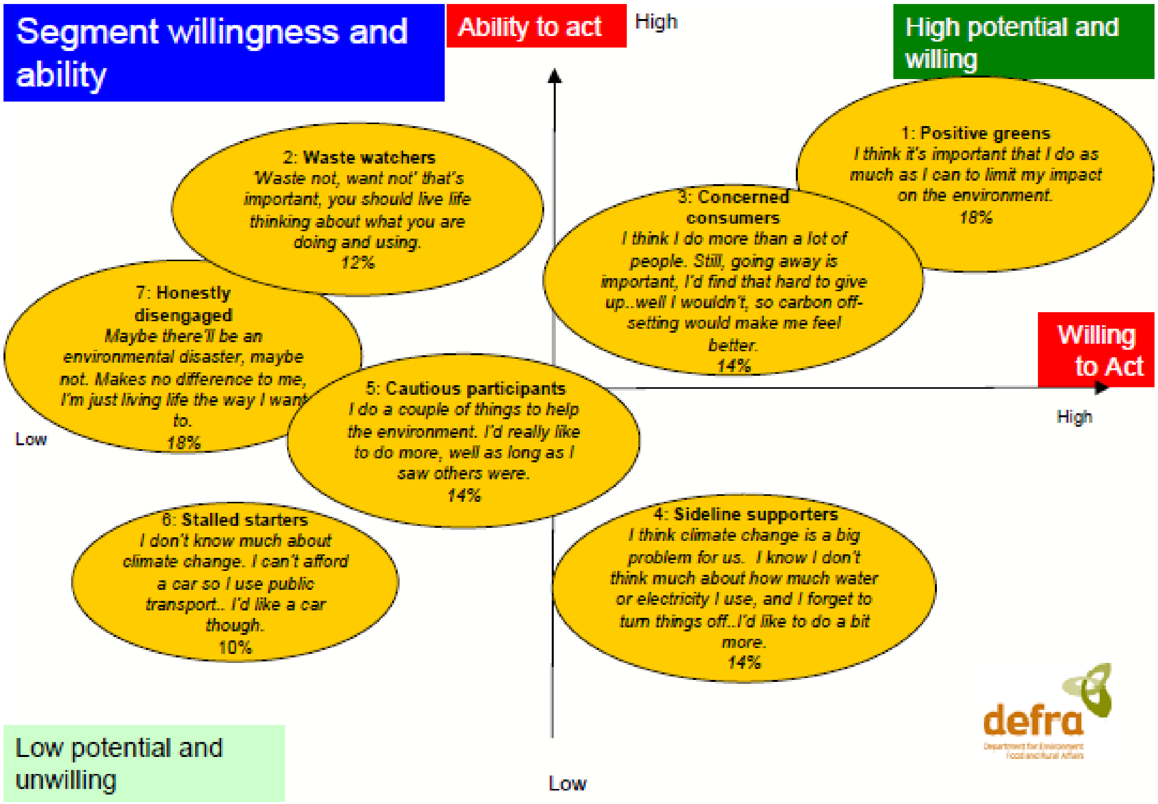


Figure 5.4 Overview of behaviours framework [33]

5.3 Methodology

5.3.1 Introduction

The primary sources of data for this chapter were the qualitative workshop transcripts from work package 2 of the UKERC funded project "Transforming the UK Energy System: Public Values, Attitudes and Acceptability" [36], and the quantitative survey results from work package 3 of the same project. The workshop transcripts are not in the public domain, due to issues of participant confidentiality, and the quantitative survey results are published at [37].

5.3.2 Transforming the UK Energy System: Public Values, Attitudes and Acceptability

A grant bid for £469,757.92 (80% of total cost) was prepared under UKERC's Funding Round 2 in 2010, led by Cardiff University's School of Psychology and supported by the University's School of Engineering and Welsh School of Architecture, as well as the Horizon Digital Centre based at the University of Nottingham. The bid was approved with a start date of 01 January 2011 and a duration of 24 months.

The research study sought to examine public values, attitudes and acceptability towards projected transformations in the UK's energy system, made in response to policy objectives including reducing greenhouse gas emissions, affordability and security of supply.

5.3.2.1 Structure of project

The "Transforming the UK Energy System" project is made up of three interlinked work packages:-

- WP1 Scenario Adaptation, Expert Consultation and Materials Development
- WP2 Deliberating Energy System Scenarios and Trade-offs
- WP3 Decision Pathways for Whole Energy System Transformations

WP1 Scenario Adaptation, Expert Consultation and Materials Development

The initial work package was designed to produce energy system materials to be used to inform WPs 2 and 3 with technically robust and plausible scenarios. Work areas proposed in the application included an analysis of existing scenarios to identify the key issues to be incorporated within WPs 2 and 3, interviews with experts from policy, industry, academia and third sector organisations for input on technical feasibility of scenarios. The research team decided to utilise DECC's My2050 online tool during WP2 as a basis for engaging public participants with the issues surrounding future energy supply and use.

Outputs under WP1 were:-

i) Technical data sheets on different technologies and policy issues by Cardiff School of Engineering (author/researcher produced data sheets on - biomass, business energy efficiency, combined heat and power, electric vehicles, energy storage, new nuclear, smart grids, smart meters and wind farms)

ii) Energy Information File

iii) Technical input into My2050 descriptors

iv) Telephone interviews held with expert stakeholders

v) Advisory Panel meeting held

WP2 Deliberating Energy System Scenarios and Trade-offs

WP2 involved the design and delivery of a series of public workshops in different locations throughout the UK. Each workshop was facilitated by two main facilitators and supported by two media operators/researchers and one technical support. Additional participants, including the Principal Investigator, and observers, including members of the WP3 team, also attended a number of the workshops. With the exception of the technical support (School of Engineering – author/researcher) all research staff were representatives of the School of Psychology.

Three pilot workshops were held in Cardiff to assess materials from WP1 and to test and revise the deliberative methodology used in the workshops. The pilot workshops were followed by seven one-day workshops as follows:-

-	22/06/11	London
-	11/07/11	Edinburgh
-	28/07/11	Cardiff
-	29/07/11	Merthyr Tydfil
-	03/08/11	Sellafield (Cumbria 1)
-	16/08/11	Glasgow (participants drawn from South Lanarkshire)
-	12/10/11	Sellafield (Cumbria 2)

With the exception of Sellafield (only six participants attended each workshop due to initial recruiter default), between ten and eleven participants attended each workshop. Participants were recruited by a professional recruitment organisation from a diverse range of social positions (e.g. gender, age, income, ethnicity etc) and were representative of the geographically diverse locations. Payment of £100 was made to each participant at the end of each workshop.

A generic protocol was used at each workshop, which were each held over one full day, with the following agenda:-

- Presentation on why there is a need for energy system change
- Questionnaire 1 on climate change, affordability and security
- Presentation on whole energy system
- Questionnaire 2 on attitude to energy saving actions and different generation technology development
- Presentation on scenarios and introduction to My2050
- Facilitated small group (5-6) discussion using My2050 tool
- Presentation and facilitated small group discussion of 3 possible scenarios (vignettes) i.e. “business as usual”, “mixing it up” and “low carbon living”
- Questionnaire 3 replicating questionnaire 2

The main outputs under WP2 were a full transcript of all seven workshops and the “Deliberating Energy System Transitions in the UK” report [38].

WP3 Decision Pathways for Whole Energy System Transformations

WP3 involved the design and delivery of an online survey to examine perspectives of various publics across the UK on whole energy system transformations. The online quota survey was carried out between 2 and 12 August 2012, of 2,441 Ipsos MORI panellists aged 18+ years old living in GB, and in accordance with the Market Research Society (MRS) Code of Conduct. The data were weighted by age, gender, region and working status to known population profiles.

The main outputs under WP 3 were topline results of the survey and the “Summary findings of a survey conducted August 2012” report [37].

5.3.3 Author/researcher contribution and methodology

The author/researcher was engaged in the development of work package 1 materials (including the preparation of technical data sheets on biomass, business energy efficiency, combined heat and power, electric vehicles, energy storage, new nuclear, smart grids, smart meters and wind farms), attended all the work package 2 workshops (apart from the second reduced workshop in Cumbria), and contributed to the development of work package 3 survey questions.

Datasets from the UKERC project cover a wide range of energy related topics and an initial exercise was carried out to filter results to those relevant to the three research questions to be addressed under this chapter:-

- what relationship do domestic consumers have with their electricity consumption?
- how acceptable is appliance automation to domestic consumers?
- what incentives would encourage domestic consumers to engage more with their electricity consumption?

The relevant quantitative survey questions were identified as nos. 40, 41, 42, 43, 45, 46, 47 and 49.

The 1,250 pages of workshop transcripts were highlighted to identify discussions and comments relevant to the research questions, and further filtered to identify themes under each heading. Comments were then selected to represent the key themes and a narrative produced to give clarity. Names of all participants have been changed in this thesis to protect their anonymity.

5.4 Results

5.4.1 Domestic consumers' relationship with their electricity consumption

5.4.1.1 Quantitative survey results

The quantitative survey results show that 50% of respondents think a fair amount or a great deal about their electricity use whereas 49% don't think very much or not at all about it (ref Q41).

Q41. How much time, if any, do you currently spend thinking about the electricity that your household uses?

A great deal	6%
A fair amount	44%
Not very much	43%
None at all	6%
Don't know	1%

However, 79% indicated they would be willing to think a little or a lot more about their electricity use (ref Q41a).

Q41a. How much more time, if any, would you be willing to spend thinking about the electricity that your household uses?

A lot more time	8%
A little more time	71%
None at all	15%
Don't know	5%

There was an interest in receiving further information about their electricity use (ref Q42) with 74% believing this would help them reduce their electricity use (ref Q43).

Q42. Smart Meters. Please indicate whether you would be interested in obtaining any of this information about your own electricity use.

Which appliance is using the most electricity	71%
Electricity usage by appliance	69%
How much you are spending on electricity at a given time	67%
Overall electricity use	65%
Patterns of electricity use over a day, week, month, years	59%
Electricity usage by room	52%
Information about how much electricity is used on average by people in homes like yours	42%
Other	3%
None of these	8%

Q43. How much, if at all, do you think having this kind of information would help you reduce your electricity use?

A great deal	25%
A fair amount	49%
Not very much	18%
Not at all	4%
Don’t know	4%

5.4.1.2 Qualitative workshop results

The qualitative workshops produced a range of comments on the different types of relationship participants have with their electricity consumption. Themes include the impact of habitual behaviour, the role of education and awareness, and how cost, comfort and environmental concerns affect the way consumers view their electricity use.

Impact of habitual behaviour

There were many comments stating that habits have an influence over everyday actions and behaviours, and that habits remove the need for conscious thought about aspects of energy consumption. Also, once habits have become established, they are difficult to break.

> Gregor (Glasgow):- It is, it's total habit and that's the biggest hurdle I think for people

> Will (Merthyr):- Maybe, but I don't know, when you get into that habit it is very difficult to break. It is very difficult to break habits isn't it? Once you're into that way of doing things I do it my way they do it their way it's very difficult for me to do them any other way

> Caroline (Cardiff):- …our practices what we do day to day, turning on and off of lights things that we take for granted but actually if you wanted to change them it's quite a difficult thing to do

There was, however, an appreciation that habits can also lead to a reduction in electricity consumption whilst retaining the characteristics of an automatic action.

> Mike (Cumbria 2):- …. So if for 5 days you told yourself I will turn everything off at the plug when I'm done. Before you know it you won't even think about doing it. And it's just I don't know, it's just like programming yourself to do certain things isn't it?

Examples of habitual consumption

A number of different examples of habitual consumption were given ranging from an automatic action when boiling a kettle, to the use of television and radio as a form of social "company" even if in the background and not the main focal point.

> James (Glasgow):- Yeah I've got a habit, I must admit, I have got a bad habit. I can switch lights off, I will not leave a light on if I don't need to, if I'm coming out the toilet, lights off, if I come out of my bedroom the lights off, but when I boil the kettle, as soon as I boil the kettle, pour my coffee, I then fill the kettle again and I boil it and walk away. And I may not be back to it in an hour, for an hour, but it is a habit, it's like compulsion! I've got to put that kettle back on, re-boil it...

> Tina (Glasgow):- I sleep with the television on. … I'll go and do something and the televisions on, I'm guilty with the television… I'm quite conscious of the lights and things, I'll put them off but my television, that's my company.

Suzanne (Cardiff):- I have to admit I hold my hand up I am a TV addict, as soon as I come in the TV goes on

Gwen (Glasgow):- Or if I go to the shop I just leave the telly on because the dog doesn't like the peace and quiet so I leave the telly on

Moderator:- The dog?

Thrift and avoidance of waste

The foundation of these habits pointed towards deeper values held by the participants. An example of this is a general attitude to thrift and the avoidance of waste, and the impact this has on habits involving electricity consumption.

Carol (Cumbria 1):- I don't remember ever being specifically taught about it, but I think it totally depends on the way you are brought up. If your parents aren't wasteful then you're not going to be wasteful. My mum and dad do switch things off, it is just common sense. I think it's just a certain amount of people who don't really care, they are not just wasteful with power, they are wasteful with everything – it's just differences in people and their opinions – maybe it's just ignorance. It wasn't drummed into me at school, definitely, it was just something you pick up from home. We were never taught about it.

These values were also linked to ideas of differences between generations and that members of older generations were more likely to be more conscious of their (electricity) consumption than younger people.

Mary (Glasgow):- … so I think the older generation did it that way, they economised that way because they were canny. In Scotland we call it canny, they watch what they were doing and they didn't waste, whereas in this day and age the kids come in, they've got the bath running, the heating's on, the hi-fi's on, the telly, my granddaughter comes in, she goes out to play and everything's on. Everything's getting charged.

Eileen (Glasgow):- I'm saying the older generation again used, they always switch off the lights if you're not using the room, you switch off the television, you switch off everything

Helle (London):- I think it is a generational thing, I mean my grandparents do that as well, and I get told off all the time for leaving lights on and stuff, but we have been brought up just not to think about it, it's there…

However, this view was not universally recognised.

Corinne (Glasgow): - But yet , I have got a 25 year old and she has got her own flat but yet she is very conscious of conserving. And she has got a really good job and it is not the money or anything like that, but it is just the fact that again at school they were taught a lot about the wasting the energy and everything at school. And she doesn't and she'll come out a room and she'll switch the light off it. Do you know, things like that? And she'll only, say the laundry and things like that? She wouldn't do like a small amount of laundry every single day, she'd only do once or twice a week like a bigger amount. So I don't know as you said [Corinne motions towards James] , I think it is the education of the person rather than the generation.

Education and awareness

The perceived lack of accessible information allied with the habitual aspects of consumption contributes to a lack of awareness of electricity use. A number of comments were expressed by participants regarding the importance of education in raising awareness.

Andrew (London):- You don't think of it as a commodity, you just think it is there

> George (London):- I wouldn’t really know where to start but that just shows not my naivety towards it but also my age, I have never worried about it and I’ve never thought I would have to worry about it but I am starting to worry about it now, I’m like, “What do I do? What do I turn off?”, when do I turn things back on? I’d be one of those annoying people saying, “Do I turn the fridge off?”, like I wouldn’t know, you wouldn’t know where to begin so for me I think that’s kind of like an age thing for me

> Gregor (Glasgow):- That’s it aye, we’re all guilty of wee things like that and you don’t think about it, … , you just go automatically into it and I think what could be done is have more education on, with, for adults like ourselves

Children and impact

The importance of formal education in raising awareness , particularly at a young age, was frequently commented on, not just for the development of the children’s knowledge but also the effect of increasing awareness within their homes containing other family members.

> Elaine (Cumbria 1):- I think children do have education at school and it is really important because my sisters - their children are coming back already and they go around and they switch off everything and it is what they are taught. One came back with an electricity counter that they were told to plug in and it showed you how much… and they went around and they had to go back and tell about the different appliances – how many units of this and units of that so I think children are becoming very aware and bringing that back into the home.

Limitations of this type of intervention were also recognised by a number of participants.

> Mary (Glasgow):- … but they are only into it for that wee while they're doing the project, you know they're doing a project in school and, "oh put the lights off" and then 3 months later they are then into zoo animals and it's, "oh save the panda", and the electricity's forgot all about.

Multi occupancy potential for conflict – negotiations

The multi occupancy nature of many households raised complex issues of negotiations over electricity consumption between different members and the potential for conflict.

> Julie (Cardiff):- … my husband is always shouting that our house is like Blackpool illuminations [laughter from group] and trying to educate the kids to turn the TV's off, and it is silly coz there are TV's in pretty much every room …

> Stan (Glasgow):- My dad used to follow me to actually put the lights off, when it was night when I was in my bed, my dad used to make sure everything was off, I mean like a night watchman. Honestly.

Bill payer – change in behaviour

The household member attempting to persuade other occupants to reduce their consumption was implied to be the electricity bill payer, and this was emphasised through comments about behaviour change where an individual became responsible for paying the bill. This supports the theory that financial factors can influence the way consumers use electricity.

> Rosemary (Edinburgh):- When my son bought his house I was totally amazed as he used to sit at his computer, and the computer was left on all night, the telly was on all night, fire left on, but when he got his own house, he's got the meter, and when he was boiling his kettle he was watching how quickly it was going around, and in his own house he will put on his gas heating for half an hour and he will lie under a quilt for the rest of the night, but he didn't do that at home, he wouldn't have thought of doing that at home but now he is paying for his own electric and gas he is quite willing to compromise.

Apathy and insignificance of individual actions

In some instances a lack of awareness of how electricity was consumed resulted from a conscious decision based on a belief that individual actions, and the amount of electricity used by individual household appliances, were not significant enough to justify the effort involved in modifying consumption behaviours.

> Joe (London):- But sometimes even the savings you make it's insignificant, we're talking about you'd be saving £10 in a year, it looks ridiculous, it's so small, so one doesn't bother.

> Neal (Cumbria 2): That's part of my stumbling block. I could make so little difference by myself. In a sense why should I bother?

> Graham (Cardiff):- It's true but the reality is I am not going to worry about it as I am here for x amount of years I'm not going to worry too overly about it. I recycle and I try and get energy efficient driven by other factors but I am also aware that unless countries like China and the big boys come on board whatever I do is actually irrelevant, even if the whole of Britain does it, it is pretty trivial. But you could argue then, that if the world sees a country like Britain doing it then maybe they will start doing it as well. So...

Cost, comfort and environmental concerns

Participants who paid a higher level of attention to their electricity consumption tended to be driven by a desire to reduce cost. This affected decisions on appliance purchase and also appliance use.

> Graham (Cardiff): If I am going to buy a new electrical item then yes of course I will get one which saves me money and not cost as much to run, but at the moment I am conscious of the environmental issues, and I do all I can

> Linda (Cumbria 1): I have now started to switch off my SKY and TV at night, I don't have anything on. I turn my washer off unless I actually need to use it - just bits and pieces like that to try and keep the cost down

> Andrew (London):- I tend to take notice of energy saving when a monetary value is put on it. If you see information like if you put your TV to off instead of standby, it can save you that amount each year, then you think, "Ah, then I'm more likely to do it". I know putting it off instead of standby saves energy, but I don't do it all the time but as soon as you know there is a monetary value to it you can relate to it more.

Other participants, however, viewed personal comfort as a higher priority than reducing costs.

Nick (Edinburgh):- No I won't, I won't put on more layers that's what I'm saying. It's at the bottom of my priority to sacrifice to help the environment is my central heating in my house, I'm not willing to sacrifice me sitting and being warm in my flat. People say put on an extra jumper, I say no I want to sit in my T-shirt in the middle of winter watching the TV with the heating on. I like sitting in my t-shirt and shorts so I'm not going to sacrifice my heating

George (London): It's about comfort

Life gets in the way

A comment from one participant encapsulated the general mood of the workshops on how many people interact with their electricity consumption.

Grace (Merthyr):- ...Information overload, … I think a lot of people don't do much, literally ignorance or speed of life, it's a thing you mean to do like this organ donation, you know **it's things you mean to do but life gets in the way**

5.4.1.3 Summary

The results show that a significant proportion of the respondents and participants have an automatic relationship with their electricity consumption based on habitual behaviour rather than conscious decision making at point of use. These habits are partly formed from basic values, such as attitudes towards thrift and the avoidance of waste, importance of comfort and cost.

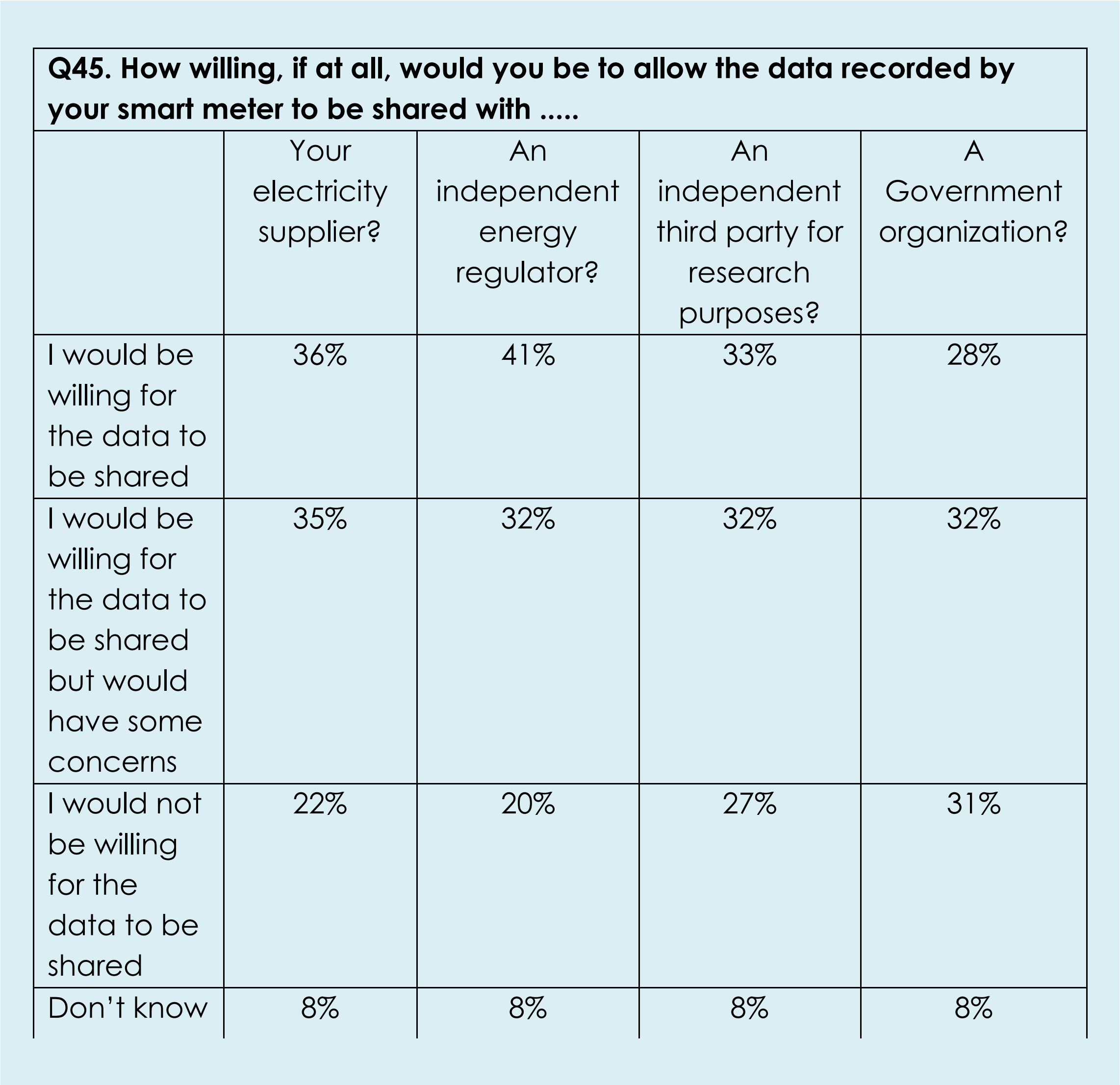
The relationship with electricity consumption was reported to vary between different members of multi-occupancy households, with the potential to cause conflict, and between different generations.

Education was seen to be important as a means of raising awareness though apathy was apparent, particularly when individual actions were seen to be insignificant in terms of environmental sustainability and cost. The expression of low levels of engagement with electricity consumption indicated the low priority this has in many participants' lives, and that other areas take a higher priority.

5.4.2 Acceptability of appliance automation to domestic consumers

5.4.2.1 Quantitative survey results

The quantitative survey results show that 78% of participants have either neutral or positive feelings about allowing electricity suppliers to have access to information from their smart meters, with 19% fairly or very negative about this (ref Q44). A majority are willing, or willing with some concerns, to allow data to be shared with other stakeholders including 73% with an independent energy regulator, 65% with an independent third party for research purposes, and 60% with a Government organisation. A significant minority (20%, 27% and 31% respectively) were unwilling for their data to be shared with these stakeholders (ref Q45).



Q45. How willing, if at all, would you be to allow the data recorded by your smart meter to be shared with .....

	Your electricity supplier?	An independent energy regulator?	An independent third party for research purposes?	A Government organization?
I would be willing for the data to be shared	36%	41%	33%	28%
I would be willing for the data to be shared but would have some concerns	35%	32%	32%	32%
I would not be willing for the data to be shared	22%	20%	27%	31%
Don't know	8%	8%	8%	8%

Attitudes towards automation of appliances varied with high acceptance of appliances being automatically switched off when not in use; medium acceptance of timers on showers and remote operation of washing machines to run at optimal periods; and low acceptance of allowing external control of cold appliances and hot water boilers (ref Q46), and allowing network operators to control appliances for network balancing (ref Q47).

Q46. Please indicate your view towards the acceptability of		
	Acceptable	**Unacceptable**
Appliances automatically switching off after set period of time on stand-by	78%	10%
Timer on showers	47%	32%
Remote operation of washing machines to run at optimal periods	48%	30%
Cold appliances being controlled externally	30%	47%
Remote operation of hot water boilers to run at optimal periods	32%	41%

Q47. How positive or negative do you feel about your electricity network operator controlling some of your appliances for the purposes of balancing the electricity grid (such as avoiding peaks in electricity demand)?	
Very positive	6%
Fairly positive	29%
Neither positive nor negative	23%
Fairly negative	22%
Very negative	18%
Don’t know	3%
Positive	35%
Negative	40%

5.4.2.2 Qualitative workshop results

The qualitative workshops produced a range of comments on the acceptability of appliance automation to domestic consumers. Themes include the principle of maintaining and ceding control, the extent of trust in external organizations, and concerns regarding the reliability and safety of automated appliances.

Principle of ceding control

There were a number of comments regarding the general principle of ceding control over domestic appliances to external agents and the degree of control individuals want to retain. These range from very negative comments to acceptance of the benefits automation and external control could potentially deliver.

> Mike (Cumbria 2):- I mean there's people out there that would probably say I would rather have a company monitor and do everything for me. There's, I know people out there for the majority of their life would like someone else to control a lot of it, and then just drift through life. Me personally I'd rather be in control of what I'm doing, what's going on. If I mess up I deal with it. If I do something right then I'm happy with it. But I just don't like the fact of someone else... Could potentially be controlling.

> John (Edinburgh):- I would have mixed feelings, but you want control over certain things that you want to do and a lot of the other people would feel the same I think, they'd want to control it rather than a supplier so I think that could be a problem for people

> Rick (Edinburgh): Look at it, if you have a laptop, if you don't use it for some minutes, it goes into standby automatically anyway, and that does not tell you that someone is automating your life or someone is controlling you, you just feel ok that is the way the appliance works, and just live with it so for me it is not the same someone just automating it.

The importance of choice and resistance to compulsion was commented on a number of times as well as practical concerns over implications of external control on other household practices.

> Nick (Edinburgh):- It's just a choice thing, political issues like giving the public a choice is bigger than the energy crisis, I agree though you have to regulate it, and give people choices within a sort of..here's your choices but what's safe and what's not..I don't think you're gonna get away with telling people what to do any more.

> Tracy (Cardiff):- The areas that I dislike is almost being told when you can do the washing, and told when you can do things, if you have got a family you can't always be told when you are to do the washing, as you have uniforms to sort out, you can't wait until the wind is good to do your washing

Trust in external organisations

A number of participants questioned the motives of external agents in relation to allowing access to domestic loads and that a profit motive may be detrimental to domestic consumers.

> Graham (Cardiff): I would be very surprised, as at the end of the day the energy companies are all about making profits, so they want you to turn your heating on and maybe I am being cynical, but they want you to have it on all day as they make more money.

Other participants were more favourable to allowing access providing this would result in reduced energy costs, though this was qualified by concerns about external agents taking more power in the future with less beneficial results for the domestic consumer.

> Mike (Cumbria):- See I wouldn't mind them knowing what was being used or what was running. I wouldn't want them to have the power to be able to turn off because it is mine and I am paying them for what I'm using. If they want to send me something and say did you know that you've got your freezer on a highest setting and it's costing you this, then I can go; oh I didn't realise that and I can correct it.

> Andrew (London): It depends what comes with it, at what cost. If it is just more sensible to run washing machines at a certain time, then I'd be fine with that, where the other control creeps in as governments and politicians often do, you just wonder if there is more to it than that.

Elizabeth (Glasgow):- I don't like to give governments too much power. Then they get overly enamoured with themselves

Technological concerns

Some participants raised practical concerns over the reliability and safety of external control and automation. These included the impact of noise on other occupants of multi occupancy buildings, and the possibility of appliance malfunction when not supervised.

Colin (Cumbria):- If my washing machine went off during the night half of Mirehouse would be out of their front door what the hell is that noise is. [giggles from group]

Rosemary (Edinburgh):- I don't know, as I say I wouldn't mind put mine on during the night but just with the fact the girl that stays upstairs has a wee baby about 3, so I wouldn't even dream of putting the washing machine on because it sounds like a rocket taking off at 2 o clock in the morning

> Val (Merthyr):- I agree, the thought of putting your washing machine on overnight is not difficult but as long as you had the option to be able to run it at other times if you wanted to, you know, you weren't only restricted to using it overnight, and as long as you had safe appliances because my husband's nephew and his wife recently lost their home when their tumble dryer caught on fire in the middle of the night.... and they just about escaped with their lives and those of the children, so safety of appliances would have to be considered as well.

5.4.2.3 Summary

Whilst the majority of respondents were willing to allow electricity consumption data to be shared with external agents there was a lower acceptance of external control of appliances. Barriers to acceptance included resistance to ceding control, dislike of compulsion, suspicion of external agents and their motives, and practical concerns over appliance safety and reliability.

5.4.3 Incentives to promote engagement with electricity consumption and allow access to flexible domestic demand

5.4.3.1 Quantitative survey results

The quantitative results show that 70% of respondents believe that National Government(s) (54%) and energy companies (16%) are mainly responsible for ensuring that appropriate changes are made to the UK energy system over the next 40 years, whilst only 13% believe that it is the responsibility of individuals and families (ref Q49).

Q49. Which one of these, if any, do you think should be mainly responsible for ensuring that appropriate changes are made to the UK energy system over the next 40 years?	
National Government(s)	54%
Energy companies	*16%*
Individuals and their families	*13%*
Environmental groups	*3%*
The European Union	*3%*
Local Authorities	*2%*
None of these	*1%*
Don't know	*8%*

Of the 81% of participants who want to reduce their energy use (ref Q40), financial reasons account for 82% of their motivation including 58% who combined this with a concern for climate change (ref Q40a). 74% of participants believe that increased information about their own electricity use (through smart meters) would help them to reduce their electricity consumption whereas 22% believe this would not be helpful (ref Q43).

Q40a. Please indicate which best describes why you want to reduce your energy use?		
1.	*I want to reduce my energy use because it will save me money*	*13%*
2.		*11%*
3.	*I want to reduce my energy use because it will save me money and will help prevent climate change*	*58%*
4.		*11%*
5.	I want to reduce my energy use because it will help prevent climate change	*6%*
To save money		*24%*
To reduce climate change		*17%*

Q43. How much, if at all, do you think having this kind of information would help you reduce your electricity use?

A great deal	25%
A fair amount	49%
Not very much	18%
Not at all	4%
Don’t know	4%

5.4.3.2 Qualitative workshop results

The qualitative workshops produced a range of comments on the different types of incentives and motivations affecting the participants' electricity consumption. Themes include the degree of personal responsibility they feel for initiating changes and the role of external agents, the degree to which governments should be involved, the role of financial and non-financial incentives, and forms of enablers and how the way in which the issues are presented can have an impact on persuading consumers to have a greater engagement with their electricity consumption.

Responsibility and freedom of choice

A number of different comment were made regarding the extent to which individuals feel it is their responsibility to become more engaged with their electricity consumption. Whilst there was an understanding that individuals have a part to play, many participants felt that the main responsibility lies with government and big business, which supports the findings of the quantitative survey. This was partly driven by a belief that actions taken by an individual or household are insignificant in the context of global climate change and national and international energy use.

> Viv (London): -Well who else is going to do it (apart from Government)? You can't expect people to do it, I mean I do my bit, but with the China scenario in the back of my mind sometimes I think what is the point. But obviously it has to be done, so it has to be done from somewhere higher

> Nicola (Cardiff):- We can do the little bits, but it is the major ones, the businesses, companies and the politicians will have to decide. We can do little things like turn off the TV but the major people and businesses ... have got to change

Despite this there was also a recognition that individual action is important with Government having responsibility to educate and coordinate.

Linda (Cardiff):- ... part of it is being able to educate people and getting people to be responsible for what is actually happening..., because one person can't be responsible for what's happened. Tens of millions of people all over the globe have added to this ... but I think if everybody does a small part - and it's the small changes that lead to the bigger changes in the long term ...: and even if the people don't think they are important, they are because they contribute, they use something every day so I think it is everybody's thing really.

Nick (Edinburgh):- At the end of the day although we say we are free, we have always been governed by somebody. We've got a government in place and I think the buck's got to stop somewhere and I think the governments got to say somewhere along the line we've made a mess with the energy situation, I know it's always been on our minds for the last 30 years, but now it is a serious issue, and I think the government have got to say look we've made the mistake here and it's up to them to give us advice

The way in which Government carries out this role drew a number of different comments ranging from resistance to any interference, considered as a threat to a citizen's liberty, to a recognition that compulsion may be necessary.

Rick (Edinburgh): This is a free society it's all about the voice of demand and supply, where if you can afford it then use it, if you cannot afford it because you know what your costs is saying then you are at liberty to turn off your lights. If they start regulating this and that, then they are taking the liberty, the freedom of choice from adults and individual we are all free to do.

Elizabeth (Glasgow):- Well it should be voluntary yes, rather than forced, but I know that they certainly want you to take these things that tell you how much you're using energy wise at the moment, I mean these are actually on the go just now

Viv (London):- It is awful, but it is very hard to ask people to do things for the greater good, especially when you have China lurking at the back of your mind, so unless there is compulsion, I think it is not going to work.

Recognition of the complex role of individual actions in mass behaviour was also apparent.

> Adrian (Cumbria 2):- I've always thought that I'm not going to change my ways if it's not going to have a massive impact and until there's a massive movement of people saying right lets all get together lets all. And it's, can be seen to be happening then I'll join in.
>
> Bridget (Cumbria 2):- But if we all thought like that nothing would get done.

Type of incentive

There were a number of views expressed regarding the drivers that would motivate participants to use less energy. There was widespread use of financial terms to describe drivers of consumption behaviour though other issues such as concern for the environment, comfort and intergenerational responsibility, also played a part.

> David (Cumbria 2):- I think that (money/cost)'s the only incentive, that's where the rubber hits the road. I don't think it's right that that should the right incentive. But that's the way we're wired isn't it?

> Mike (Cumbria 2):- Because it's not, you talk about carbon footprints and you can say how they work but you can't see it... Whereas money in your pocket you can see. And I personally think that it's what everything revolves around isn't it? If you want people to reduce carbon and things like that you got to show them how they can save money by doing these things.

> Andrew (London):- I think personally, I tend to look at the cost to myself, and the benefits to myself before I consider if it is also helping any other energy efficiencies. If I can see something which would make a reduction in my bills, that would make me more likely to do it.

Financial - pros and cons

Notwithstanding the domination of cost as a stated driver, the reliance on this as the sole driver of behaviour was seen to have shortcomings including the insignificance of cost at an individual appliance level and the resulting lack of incentive to modify behaviour for financial gain.

> Graham (Cardiff):- Funnily enough this meter you've got at the bottom here, my wife foolishly got me one for a laugh and I am always telling them to turn lights off and when you actually use one of those to see, don't quote me on this but things like leaving on TVs on standby with the light on which my mum has always told me costs an arm and a leg and turning it off or leaving it on standby is negligible.

> Will (Merthyr):- If it was only a little bit of the cost, people aren't going to, I wouldn't take any notice, if I need it now and I need it now, I want it now that's the thing

Financial/environmental

A number of participants cited environmental concerns as well as cost as a driver to modifying their consumption behaviours.

> Julie (Cardiff):- Predominately cost I suppose if I am honest, but in the back of my mind it is the environmental cost as well

> Elizabeth (Glasgow):- I think about both things, I think about saving the planet and then also think about the affordability

Non-financial incentives

Other themes presented by the participants included comments regarding the importance of collective action, responsibility for the well-being of future generations, and behaving in a socially responsible way.

> Tina (Cardiff):- If you want to make a change it's a collective thing, everyone has to make a difference.

> Rosemary (Edinburgh):- If it is going to help, I want to think of my grandchildren, and their children, and I don't want them brought up in poverty because we're too selfish to switch things off standby

Lexi (London):- There is also the greater good thing, you know like with fair trade where people actually actively choose to pay a bit more because what they're doing is buying into something which is supposedly intrinsically better.

Becky (Edinburgh):- I disagree, I like what you're saying but I totally disagree on if they've got the money... My mum comes from a country where her sister used to wash until recently the clothes in the river that is how it works. Just because we have the money to go and ruin the environment I don't think we should.

Viv (London):- But nowadays everyone has to be rewarded for everything. Why can't people just do it because it is the right thing to do. You don't need an incentive

Helle (London):- No you don't, but it does make things sweeter

Mixture of incentives

A number of participants recognised that, given the diversity of values and opinions held by individual consumers, a range of incentives would be required in order to encourage a greater degree of engagement with electricity consumption.

Lena (Cumbria 1):- So a mixture of reward, penalty and appealing to peoples' nature to want to move things forward in a certain direction - that might work. It might just swing the balance if enough people sign up to it.

Presentation and complexity

A number of participants commented on the way in which the issues were presented could have an impact on the effectiveness in changing consumption behaviours. These ranged from a belief that hard-hitting advertising campaigns, with comparisons made to previous drink-driving campaigns, would be more effective, to more inviting and positive approaches.

Blair (Edinburgh):- I think the only way people are actually going to learn, is if like a global disaster happens .... To do with the drink driving .... people are starting to wear their seat belts more and all that and not drink drive because the way they are doing the adverts, like the adverts crashing into kids and all that, and if they kind of show that in adverts .... what is going to happen in the future if people don't change, people might listen. If they don't and try and be nicey, nicey with the adverts I don't think people are gonna listen

Joanne (Edinburgh): - I'm not sure to be honest, that is almost like shock tactics isn't it, and don't think I totally agree with it, I think you need a more gradual educational way of getting through to people.

Rick (Edinburgh):- Exactly, a positive thing, make it exciting, make them buy into it, voluntarily

> Stuart (Cardiff):- ...you need to address the problem in a way which is inviting for people to adopt and that there is some sort of benefit to them, whether that benefit is financially or they carry on living how they are at the moment but with a greener sort of aspect

Complexity was seen to be a barrier to changing consumption behaviours with some participants unwilling to invest effort in understanding a complicated message.

> George (London):- ... if something is very complicated, a lot of people, and I know I'm one of them, ... sometimes it is easier to switch off and stay with the norm, or what the generalized last thing is, ... when things become complicated it's easier to just go, "oh, I don't understand that"

5.4.3.3 Summary

The quantitative and qualitative results indicate there is a significant role for Government and big business to encourage individuals to become more engaged with their electricity consumption though this is countered by a suspicion of their motives and concerns about a reduction in freedom of choice.

Financial reasons were often given when considering drivers which would incentivise modified consumption behaviours. Other, non-financial, incentives were thought important when other issues, such as concerns for the environment, future generations and social equity, and the insignificance of cost at an individual appliance level, were considered. It was also recognised that different people have different values and opinions which would require a multi-pronged approach.

The way in which the issues are presented would have an impact on the receptiveness of consumers with some arguing for a hard-hitting approach whilst others preferring a more inviting message. Complexity was seen to be a barrier to encouraging consumers to engage more with their electricity consumption.

5.5 Discussion

The participants in the qualitative workshops and respondents to the quantitative survey made a wide range of comments and responses relating to the three research questions raised in this study, namely:-

- what relationship do domestic consumers have with their electricity consumption?
- how acceptable is appliance automation to domestic consumers?
- what incentives would encourage domestic consumers to engage more with their electricity consumption?

Whilst the research questions were distinct there were a number of common themes across the responses.

5.5.1 What relationship do domestic consumers have with their electricity consumption?

Effective demand side management requires demand to vary in response to an external signal. This can be done automatically, through appliance automation, or manually by household occupants modifying their consumption behaviour in a way which supports the effective and efficient operation of the electricity system. The relationship consumers have with their electricity consumption is crucial to these activities and requires a high level of consumer engagement and a willingness, and ability, to make conscious decisions about their consumption behaviours across different time periods.

The quantitative survey results, however, indicate that 49% of respondents don’t think very much or not at all about their electricity use. This is supported by comments made in the qualitative workshops which highlight that electricity use is not high on the list of many people’s priorities and when thought about tends to be in terms of overall cost rather than linked to individual appliance use. Engagement at the point of consumption is often with the energy service e.g. light, heat, entertainment etc., and for indirect purposes e.g. company and social status, rather than as a conscious awareness of electricity consumption. This automatic relationship is generated through routine and habitual behaviours, leading to behavioural “lock-in” [10], and is a reflection of the need to prioritise decision making on higher level activities.

The implications of this are that domestic consumers are unlikely to be able (or willing) to actively modify their consumption behaviour in response to external signals unless these can be incorporated into a pattern which can be adopted into a routine. This may be sufficient for persistent changes in demand e.g. peak shifting, but less effective for more dynamic responses to short term signals e.g. frequency response.

Deeper values, such as thrift and avoidance of waste, have an impact on consumption behaviours, as do generational variations. This has the potential to create conflict within multi-occupancy households where different individuals hold different values and views on consumption. An awareness that individual households are not necessarily homogeneous entities can influence the approach taken to encourage greater engagement.

The quantitative survey results show that 79% of respondents would be willing to spend more time thinking about their electricity use and that having access to more information would be an enabler to reduce consumption. The qualitative workshops were consistent with this view and there was support for the provision of formal education, across all ages, to improve levels of awareness.

The insignificance of individual action in terms of cost and on global sustainability, was apparent from the qualitative workshops with a number of participants preferring to behave in a way which maximised their own comfort rather than recognising the role individuals have in socially beneficially behaviours. Electricity market structures, which create barriers to apportioning socialised infrastructure investment costs to individual consumer actions, lead to a disincentive to invest time and effort in changing consumption behaviours.

5.5.2 How acceptable is appliance automation to domestic consumers?

Appliance automation can help deliver the necessary flexibility in electricity consumption, required for effective demand side management, where domestic consumers are unwilling, or unable, to modify their consumption behaviour in response to an external signal. This would be particularly relevant for conditions requiring a fast response such as frequency control, in a future electricity balancing market. The adoption of appliance automation to support domestic demand side management, would be enhanced by technological developments such as the introduction of smart electricity meters to allow timely communication between individual appliances and the requirement of the wider electricity system. It would also require the permission of individual domestic consumers to allow this access.

The quantitative survey results show a majority of respondents are unwilling, or willing but with some concerns, to allow smart meter data to be shared with external agents. The qualitative workshops provided some possible reasons for this reluctance, including a suspicion of these agents' motives and the possibility of the information being used in future against the interests of individual consumers.

The qualitative workshops also highlighted the importance to individuals of maintaining control over familiar consumption decisions and a reluctance to cede control to an external agent. This was also apparent in the quantitative survey results which showed higher levels of acceptability of seemingly low impact automation, such as appliances on stand-by switching off automatically after a set period of time, while less familiar actions, such as cold appliances being controlled externally and hot water boilers being operated remotely, showed lower levels of acceptability. Segmentation of load categories has also been found in other studies [e.g. 39].

These emotional responses against appliance automation were also supported by practical concerns over appliance safety, reliability and suitability for automation, which indicate that a number of different approaches will be required to increase the acceptability of appliance automation to domestic consumers.

5.5.3 What incentives would encourage domestic consumers to engage more with their electricity consumption and allow access to flexible domestic demand?

The participation of domestic consumers in demand side management, either in an active way through unique alterations to consumption or in a more passive way by permitting appliance automation, will require some form of incentive, even if that is just by being informed of the societal benefits of engagement. An understanding of the effectiveness of different types of incentive is useful for those interested in developing effective domestic demand side management.

The quantitative survey results show that only 13% of respondents believe it is the responsibility of individuals and families to ensure that appropriate changes are made to the UK energy system over the next 40 years. This was supported by comments made in the qualitative workshops which also highlighted the issue of the insignificance of individual action in the context of global climate change, national and international energy use, and cost at an individual appliance level.

A large majority of respondents to the quantitative survey stated that financial reasons were their motivation for wanting to reduce energy use. The qualitative workshops also identified cost as a significant factor affecting consumption behaviour. The importance of cost, however, reduced as the low levels of value attached to individual appliance use was identified, and other concerns were raised, such as a lack of social equity where wealthier households could afford to consume more at the disproportionate expense of a wider community. A number of participants commented that using cost as a primary incentive to modify behaviour could act as a disincentive and bring legitimacy to excessive consumption behaviour.

The role of Government to provide education and appropriate information to increase levels of awareness, was also raised in the qualitative workshops. The way in which this was delivered was seen as important with some participants favouring a hard-hitting approach while others felt a more accessible and inviting style would be more successful. The need to avoid complexity was also considered important by some.

Given the range of views expressed, and the importance of context on the effectiveness of incentives, it is likely that a number of different incentives would be required to encourage a cross-section of consumers to engage more with their electricity consumption and allow access to flexible domestic demand.

Chapter 6

Conclusions, contributions and further work

Summary:

This chapter provides a brief description of the main conclusions of the research carried out for this thesis. It also identifies the principal contributions made in the thesis and gives some suggestions for further work.

6.1 Conclusions

Energy policy is leading the electricity supply market to a lower fraction of dispatchable generation. This will increase the role and opportunities for demand side management to maintain an effective and efficient electricity system. The domestic sector accounts for more than one third of total GB electricity demand and is a potentially significant demand side resource. The extent of flexible domestic demand is limited by technological, social, economic and behavioural factors, partly due to low levels of consumer engagement with their electricity consumption.

This thesis describes:-

- potential future generating technology mixes for 2020, 2030 and 2050, which would satisfy energy policy targets
- different categories of domestic electricity demand
- flexible domestic electricity demand in 2030 and the extent to which this could be practically accessed
- the extent of consumer engagement with their electricity consumption and the behavioural barriers to accessing flexible domestic demand

6.1.1 Generating technology mix optimization

Changes in the UK’s generation mix, necessary in order for the UK to meet its emissions targets, will result in a higher fraction of non-dispatchable, renewable generators.

The development of scenarios to explore possible futures is useful in order to consider effective responses to these possible futures. Whilst “the most likely future isn’t” [Chapter 3 ref 12], the ability to “think the unthinkable” [Chapter 3 ref 8] can, in the context of the UK electricity system, provide a framework to understand the impact of changes to the generation mix, particularly the major challenge of addressing the extent of non-dispatchable generation in the future.

Models are, by definition limited in scope. The model described in Chapter 3 addresses the annual output of electricity and does not consider the relationship between instantaneous supply and demand, and the impact of supply characteristics on system stability.

The optimization carried out indicates an increase in unit costs due to the increase in more expensive, renewable technologies and the introduction of higher levels of carbon floor price, though these increases are limited due to lower capital costs of plant and improved generating efficiency. Assumptions used in the model, including costs, are, however speculative and different assumptions can produce different results.

The results show the dispatchable fraction of annual electricity output drops from 77.0% of total output in 2012, to 69.2% in 2020, 41.3% in 2030 and 28.0% in 2050. This will have a significant impact on the ability of generators to maintain a balance between supply and demand. The results also indicate that a reduction in annual demand and capacity can lead to significant savings, therefore the role of the demand side, and increased efficiency, is likely to increase in the future.

6.1.2 Flexible domestic electricity demand

The GB domestic sector is projected to account for 121.6TWh annual electricity demand in 2030. The extent to which this demand is flexible, and thus useful for demand side management, varies between different categories of appliance. GB domestic flexible demand, defined as electric space and water heating, cold appliances and wet appliances, is projected to account for 64.3TWh of annual demand in 2030 though the amount that is apparent at any point in time varies significantly on a diurnal, weekly and seasonal basis, as shown in Figure 6.1. This is due to links between household occupancy patterns and habitual appliance use, such as the use of dishwashers after meal times.

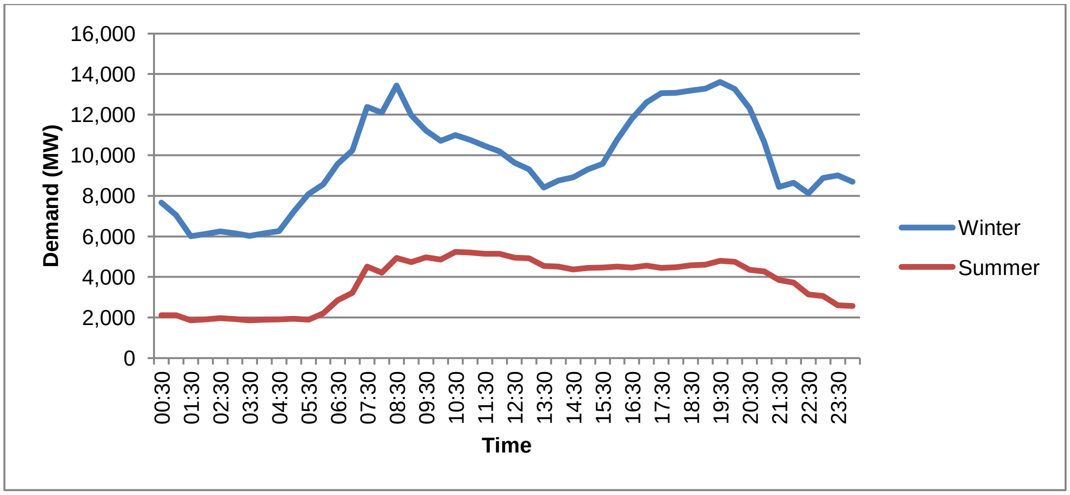


Figure 6.1 Flexible domestic daily load profile in winter and summer 2030

The amount of flexible demand which could be practically available at any point in time is also subject to permissions being granted by domestic electricity consumers to allow access to the loads. The amount of practically available domestic flexible demand in 2030 on two sample days (mid summer and mid winter) at three sample time points (05:00, 08:00 and 17:30) varies between 838MW at 05:00 in mid summer to 6,150MW at 17:30 in mid winter, as shown in Figure 6.2.

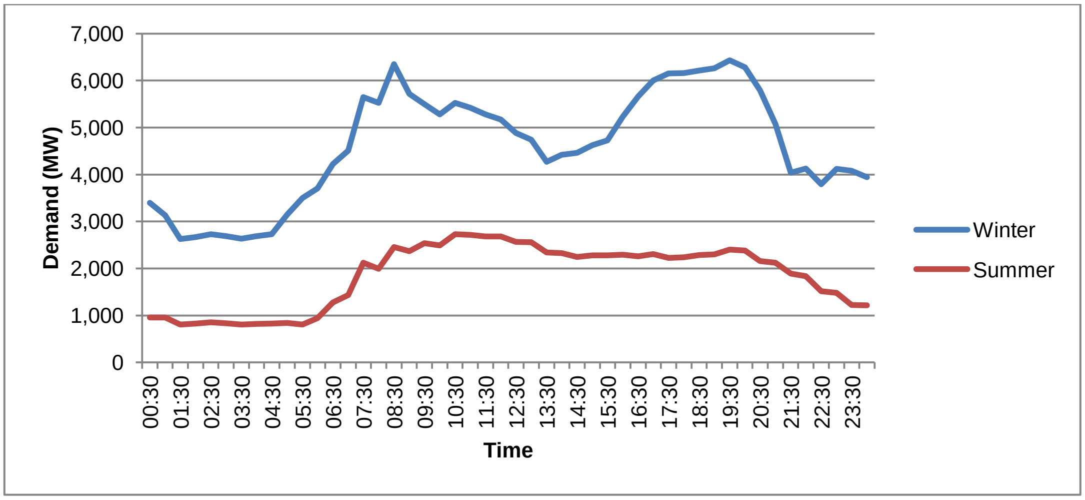


Figure 6.2 Flexible domestic daily load profile in winter and summer 2030 (practically available)

6.1.3 Consumer engagement and access to flexible domestic demand

The following research questions, relating to access to flexible domestic electricity demand, were addressed.

What relationship do consumers have with their electricity consumption?

Consumers' relationships with electricity consumption is characterized as being mainly with the energy service provided, e.g. light, heat and entertainment, and not with discrete electricity consumption choices. Habit and social practice play an important part in patterns of domestic electricity consumption. The quantitative survey results indicate that 49% of respondents don't think very much or not at all about their electricity use, and this has implications for the effectiveness of demand side management measures which rely on consumers to modify behaviour in response to a signal.

How acceptable is appliance automation to domestic consumers?

Whilst appliance automation is the practical solution to realising the demand side potential of domestic demand, many consumers express resistance to allowing remote access. Concerns are linked to a lack of trust in external agents and a reluctance to cede control, as well as practical concerns over appliance reliability and safety.

What incentives would encourage domestic consumers to engage more with their electricity consumption and allow access to flexible domestic demand?

Many consumers are motivated by financial incentives though the low value of individual appliance consumption limits the impact solely financial incentives could have. Context has an important role in the effectiveness of incentives and a range of different approaches would be required to encourage a wide cross-section of consumers to engage more with their electricity consumption.

6.2 Contributions of thesis

The contributions made in this thesis are:-

- development of an optimization model which produces a mix of generation technology capacities which satisfy emissions, diversity and economic targets
- projections of domestic electricity demand to 2030 and the identification of flexible load within the overall demand
- identification of the total amount of flexible domestic demand available at different time points in summer and winter, and the amount of load which is practically available at these times
- analysis of quantitative survey and qualitative workshop transcript datasets to address issues of consumer engagement and access to flexible domestic demand

6.3 Recommendations for further work

Recommendation for further work are described in line with the topics of Chapters 3, 4 and 5.

Generating technology mix optimization

The optimization of generating technologies in Chapter 3 has been carried out using annual energy outputs and overall capacities. The power profiles of different technologies display different characteristics, ranging from dispatchable traditional technologies, to baseload nuclear, and intermittent renewables. As the generating capacity mix changes, it would be useful to investigate how different combinations of generating technologies impact on the overall generating profile, and to highlight where demand side resources could be most useful. The modelling of power supply characteristics of different combinations of generation technology capacities, incorporating wind and solar PV generating profiles, would assist in this area.

Flexible domestic demand

Daily load profiles have been established in Chapter 4, showing unmanaged loads for flexible categories of demand i.e. electric space and water heating, cold appliances and wet appliances. Some of these loads could be moved with minimal impact on consumer utility e.g. by using thermal storage for heating and cold appliances, and by altering the timing of wet appliance operation. The extent to which it would be beneficial for loads to be moved would depend on the overall state of the electricity system and the available capacities of generation and distribution networks at different time points. Overlaying flexible demand profiles with wider system requirements would give an insight of the extent of potential savings to electricity infrastructure investment through the utilization of flexible domestic demand.

Consumer engagement and access to flexible domestic demand

The two main models for establishing the value of flexible domestic demand are the market model, using existing structures such as the balancing market, and the avoided cost and asset utilization model, which takes account of total system costs and the potential for demand side management to improve system efficiency, generation and network utilization rates, and thus avoid infrastructure investment. A barrier to offering meaningful financial incentives to consumers to participate in the market is that avoided socialised infrastructure investment costs are difficult to apportion to individual consumer actions. An analysis of appropriate market arrangements, to allow consumption behaviours which support an efficient and effective electricity system to be rewarded, would be of interest.

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