Life Cycle Sustainability Assessment of the Electrification of Residential Heat Supply in UK Cities

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Abbreviations

ADP	Abiotic resource depletion
AEA	All electric heating approach model
AP	Acidification potential
AQM	Air quality monitoring
ASHP	Air source heat pump
AVG	Average
BETTA	British electricity trading and transmission arrangements
BRE	Building Research Establishment
BTU	British thermal unit
CAP	Community analysis package
CC	Carbon capture
CCC	Committee on climate change
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CEAS	Chemical engineering and analytical science
CELECT	Electronic sensors linked to central control device
CERT	Carbon emission reduction target
CGBH	Centralised gas fuelled hot water and electric space heating model
CGEN	Combined gas and electricity network model
CHP	Combined heat and power
CoP	Coefficient of performance
CSH	Code for sustainable homes
DCLG	Department for Communities and Local Government
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DHN	District heat network
DHW	Domestic hot water
DNO	Distribution network operator
DTI	Department of trade and Industry
ECO	Energy company obligation
EFW	Energy from waste
EHCS	English house condition survey
EP	Eutrophication potential
EPC	Energy performance certificate
ERP	Energy related products
ESCo	Energy service company
ETS	Emission trading scheme
EU	European Union
EURED	European Renewable Energy Directive
FAETP	Fresh water aquatic eco-toxicity potential
FIT	Feed in tariff
GE	Greenhouse effect
GHG	Greenhouse gasses
GJ	GigaJoule
GSHP	Ground source heat pump
GW	GigaWatt
GWh	GigaWatt hours
GWP	Global warming potential
HEMS	Household energy management strategy
HTW	Hot tap water
HW	Hot water
IAQ	Indoor air quality

IGB	Individual gas boilers model
kW	KiloWatt
kW_{he}	KiloWatt hour of electrical energy
kW_{hth}	KiloWatt hour of thermal energy
kW_p	KiloWatt peak
LA	Local authorities
LCA	Life cycle assessment
LCC	Life cycle costing
LCCA	Life cycle cost accounting
LCD	Liquid quartz display
LCIA	Life cycle impact assessment
LCTP	Low carbon transition plan
LDF	Local development framework
LNG	Liquefied natural gas
LSOA	Lower super output area
MAETP	Marine aquatic eco-toxicity potential
MLSOA	Middle layer super output area
MSW	Municipal solid waste
MT	Million tonnes
$MTCO_2$	Million tonnes of carbon dioxide
MTOE	Millions tonnes of oil equivalent
MTpa	Million tonnes per annum
MW	MegaWatts
NGET	National grid electricity transmission
NPV	Net present value
NRF	Neighbourhood renewal fund
ODP	Ozone depletion potential
OFGEM	Office of the gas and electricity markets
PCA	Principal Component Analysis
POCP	Photochemical ozone creation potential/smog potential
PV	Photovoltaic
RES	Renewable energy strategy
RHI	Renewable heat incentive
ROC	Renewable obligation certificates
ROO	Renewable obligation orders
SAP	Standard assessment procedure
SH	Space heating
SNG	Substitute natural gas
SPD	Supplementary planning document
SPSS	Statistical package for social sciences
SPTL	Scottish Power Transmission Limited
TER	Target Carbon Dioxide Emission Rate
TETP	Terrestrial ecotoxity potential
TO	Transmission owner
t	tonne
TWh	TeraWatt hours
UK	United Kingdom
UKERC	UK Energy Research Centre
UN	United Nations
W	Watt
WEEE	Waste electrical and electronic equipment directive
WCED	World Commission on Environmental and Development
WHO	World Health Organisation
WSHP	Water source heat pump.

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Abstract

The recent revival of urban living in the UK has been stimulated by many different factors, including life style choices and government policies. This has led to a rapid increase in the number of apartments in the UK cities. This increased density living has also brought about various changes in the city infrastructure, including the way energy is supplied to residential buildings. The recent trend of 'electrification of heat' represents one of these changes, whereby electricity rather than natural gas is now typically being used for space and water heating as well as for cooking. Further growth in electricity demand has been predicted in the governments *Carbon Plan* with the increased use of all-electric systems including heat pumps for domestic heat. This will in turn impact the environment since electricity supplied in the UK is predominantly based on fossil fuels and contributes to significant greenhouse gas (GHG) and other emissions. However, greater penetration of renewable sources in the future would be expected to reduce GHGs. This would also help to improve the security of supply through diversification of energy sources. On the other hand, there are concerns that increasing reliance on electricity could lead to fuel poverty for a greater section of society. Thus, it is not immediately clear whether the change from gas to electricity would contribute to the sustainability or otherwise of energy supply in the UK residential sector.

Therefore, this research has set out to understand better the implications of the electrification of heat in the urban residential sector by examining the trade-offs between environmental impacts, techno-economic costs and social aspects. This work therefore goes beyond the previous research that has typically focused solely on GHG emissions and energy pay-back times of different energy options. This is also the first time as far as the author is aware that the sustainability of the electrification of heat in cities are analysed in depth. Various tools have been used for these purposes, including life cycle assessment (LCA), indoor air quality monitoring (IAQ), life cycle costing (LCC), social surveys (SS), scenario analysis (SA) and multi-criteria decision analysis (MCDA).

Assuming all sustainability aspects considered here to be equally important, the most sustainable option is the district heating system. All-electric heat-providing systems (electric panel, electric storage, and air source heat pumps) have on average 2.5 times higher environmental impacts than gas-based systems (individual gas boiler, solar thermal and gas, district heating and community CHP systems). The techno-economic costs of all-electric systems are 80% that of the district heating system – however, fuel cost and demand changes increase substantially all-electric system cost vulnerability. Gas-based systems are widely accepted and valued - all-electric systems while a 'good fit' for particular city homes - have greater social impacts including affordability.

If the proposed decarbonisation of electricity generation is realised, the global warming potential from electric heat-providing systems could be reduced to a $1/10^{th}$ of present emission levels by 2050 increasing electrification of heat sustainability.

Therefore, the choice of the most sustainable heat-providing options in the future, including that of the 'electrification of heat', will depend on the extent of the decarbonisation of the UK electricity supply and the relative importance placed on sustainability impacts by different stakeholders.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Copyright Statement

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1. Introduction

In 2001 around 80% of the UK population lived in urban areas (Gask, 2005), predominantly in flats and apartments (Bromley et al., 2007). Overall, of the 22.3 million homes in the UK, some 4.93 million are flats and apartments with 792,000 situated in city centres (CaLG, 2007c; CaLG, 2011). The increase in urban living has been stimulated by government policies (CaLG, 2000a) but is largely driven by life-style choices. The rapid growth in the number of flats and apartments in the UK cities has led to various changes in the city infrastructure, including the way energy is supplied to residential buildings. The recent trend of 'electrification of heat' represents one of these changes, whereby electricity is now typically used for space and water heating rather than natural gas (Olivier, 2007).

Electricity used by the domestic sector contributed to around 30% of the overall UK electricity use in 2012 (DECC, 2013b). Recent proposals suggest the electrification of both passenger transport and household heat provision (DECC, 2009c); this implies that electricity generation capacity will need to increase to cope with these demands. However, the UK government has also set targets to reduce carbon emissions by 80% relative to 1990 levels by 2050 (DECC, 2009c), through investment in energy efficiency and clean energy technologies such as renewables, nuclear and carbon capture and storage (CCS) (CaLG, 2007a). To help achieve this CO_2 target, 15% of the UK energy will have to come from renewable sources by 2020, and for this target to be met, 30% of electricity generated will need to be generated by renewables by this date with a complete decarbonisation needed by 2050 (UKERC, 2009b). Currently though, the UK electricity is generated from a mix of predominantly fossil fuels, including coal and gas as well as nuclear; a small but growing proportion comes from renewables (DECC, 2009b). Due to its reliance on fossil fuels, electricity is a significant source of greenhouse gas emissions (GHG) and other air pollutants such as acid gases and particulates (EFRA, 2006). Any significant switch from natural gas to electric heating could mean displacing environmental impacts from cities (from the combustion of gas in boilers) to rural areas where power plants are normally situated (Luickx et al., 2008). Conversely, the decentralisation of electricity production to smaller, more localised, plants could shift such impacts back into urban areas.

The increased use of building thermal insulation, improved glazing and other energy efficiency measures can have a profound effect in reducing energy demand (Guertler and Smith, 2006) resulting particularly in space heating reductions (ODPM, 2006a). However, increasing household demand for hot water and cooking can result in greater electricity demand (Torekov, 2007). Such efficiency improvements along with gas safety concerns and building regulation changes have previously promoted electric heating (CaLG, 2008b); this has also gelled well with building developers' desires for low cost heating system installations. Recent and planned improvements to the building regulations (CaLG, 2007a) now make it more difficult to use electric for heating alone in high density developments such as apartment blocks. Nevertheless, heating technologies exhibiting improved performance and efficiencies including heat pumps and modern electric resistance heaters continue to support the electrification of heating.

Previous studies have focussed on improving the sustainability of future UK energy supplies to homes and industry (DTI, 2006a; OFGEM, 2009; UKERC, 2009a) while others, (Ferreira, 2007; Gustavsson and Joelsson, 2008; Monahan and Powell, 2010; Prek, 2004; Blom et al., 2010) have considered primary energy use and mixes for heating systems in residential buildings. Elsewhere, (Blom et al., 2010; Prek, 2004; Gustavsson and Joelsson, 2008; Shah et al., 2008) have studied the life cycle contributions and use of residential heating and cooling systems although few have studied the supply and utilisation in the context of city dwellings and specifically the life cycle impacts of an energy switch and electrification of heat.

This research, therefore, examines the environmental, techno-economic and social impacts of the electrification of heat on a life cycle basis.

1.1 Project aims, objectives and novelty

This research has developed a novel approach to assessing the sustainability of city heat-providing systems taking into account environmental, techno-economic and social dimensions of sustainable development. The specific objectives of this research have been:

- to compare and contrast the environmental, techno-economic and social sustainability of current and possible future gas and electricity supply to city households in the UK in order to identify impacts of the electrification of heat;
- to develop an integrated life cycle sustainability assessment framework and indicators applicable to the electrification of heat;
- conduct sustainability assessment using this methodology which comprises a range of tools and approaches including - life cycle assessment (LCA), air quality monitoring (AQM), life cycle costing (LCC), social surveys (SS), multi-criteria decision analysis (MCDA) and scenario analysis (SA);
- to identify most sustainable options and make recommendations related to the electrification of heat; and
- to make policy statements based on the results of the sustainability assessment.

The main novel features of this research include:

- the integration of environmental, techno-economic and social assessment tools and indicators into one framework capable of quantifying the level of sustainability of the electrification of heat, both at the technology and energy system levels;
- a first full life cycle sustainability assessment of heat-providing systems in the context of UK city dwellings and specifically the life cycle impacts of an energy switch and electrification of heat.

1.2 Thesis structure

The remainder of the thesis is structured as follows: Chapter 2 provides a literature review that examines the context, policies and drivers concerning the electrification of heat as well as the sustainability of energy networks and technologies related to heating and electricity supply in UK cities. A further section considers social sustainability and air quality monitoring. Chapter 3 details the methodology developed and used in the research and includes a discussion of the various tools, models, indicators and scenarios that are used. Chapter 4 presents the work conducted on environmental sustainability including life cycle assessment and air quality results. Chapter 5 focuses on economic sustainability of the systems and Chapter 6 social sustainability. Chapter 7 conducts a multi-criteria decision analysis of the studied heat-providing systems to help identify most sustainable options. Chapter 8 presents the scenario analysis of energy supply up to 2050. Finally, Chapter 9 outlines the conclusions, recommendations and further work of the study.

The thesis also includes appendices containing life cycle inventory tables and supporting information for the sustainability study, stakeholder questionnaires, indoor air monitoring, and case study background details.

2. Review of electrification of heat, heating technologies and sustainability

2.1 Electrification of heat

The electrification of heat is the change from using natural gas for cooking, space and water heating to using electricity. This energy type change has been most clearly recognised within city centres and urban areas where the proliferation of new apartment developments has encouraged the sole use of electricity for residential use as opposed to natural gas (Olivier, 2007). The electrification of heat as a trend or phenomenon has not been clearly identified to date within energy-related literature; but it has been alluded to through energy demand changes (BERR, 2007a), manufacture data (AMA, 2009a) and new housing development information (AMA, 2009b). The impacts of the electrification of heat have been studied by comparing gas and electricity energy consumption in the US (Bodansky, 1984) and through an evaluation of fuel-switching opportunities in the residential sector in Portugal (De Almeida et al., 2004). UK studies have concentrated on CO_2 emissions from gas and electric heating technologies with results implying a shift towards greater use of electricity for domestic heating (Cockroft and Kelly, 2006) or an 'all electric' future (ICEPT and CES, 2010).

This review of the literature examines the historical perspective and potential drivers for the electrification of heat, as well as the implications for the supply of electricity to cities. The review also considers the literature that has researched the sustainability of various heating technologies currently being used in homes and those that may be used in the future.

2.1.1 Historical perspective

Unprecedented economic growth after the Second World War rapidly increased the demand for electricity in the UK. Industries were nationalised and focussed on improving efficiency and subsequently improving living standards including heating and the availability of electrical appliances (Dzioubinski and Chipman, 1999). Electricity however remained more expensive to use than gas until people began to move into homes that were pre-wired for electricity use (MTMW, 2011). The construction of the national electricity grid and super-grid brought electricity to nearly all of the UK population by the 1950s. Electric fires became widely available in the 1950s and were popular for heating due to their portability. Within homes, off-peak electricity rates were introduced to flatten the load curve and improve use of the electricity production system (Grid, 2012). The use of gas for heating and particularly central heating increased with the discovery of natural gas in the 1960s and Britain's conversion from coal gas to natural gas by the mid 1970s. During the 1990s there was a 'dash for gas' to provide new supplies to more isolated towns and villages for household central heating. In addition, gas was chosen as the prime fuel for a new generation of power stations (Winskel, 2002). This trend continued despite reduced indigenous supplies of natural gas and an increasing dependence on imports. In 1970 only 10% of households were centrally heated by gas in Great Britain - by 2000 this had increased to 75% and overall nearly 85% presently have central heating (DECC, 2009b). Dzioubinski and Chipman (1999) suggest that there have been two opposing trends in developed countries regarding household energy consumption since the 1970s. The first is the increase in energy based living standards through increased incomes and the second is the reduction in energy usage due to reduced space and water heating demands and improvements to residential building thermal properties. Heating by electricity has taken advantage of this trend through the recent installation of electric panel and storage heating and its suitability in modern residential buildings.

2.1.2 Potential drivers for the electrification of heat

2.1.2.1 City redevelopments

Encouraged by government policies and statements (CaLG, 2000a) to promote city centre living and to increase residential land use on brownfield sites, there has been considerable repopulation of the city centre and urban areas (Bromley et al., 2007). Whilst any definition of an urban area is complex, in England and Wales it relates to land comprising of permanent structures, transport corridors and features, and is surrounded by built up sites extending for 20 hectares or more (NSO, 2001). In England and Wales this typically refers to an area with >10,000 people (Pointer, 2005). Consequently, around 80% of the population in the United Kingdom lived in an urban area in 2001, with nearly 41 per cent living in one of the UK ten most populous cities

(Pointer, 2005), including London, Birmingham and Manchester. To provide homes in these cities, a considerable number of flats and apartments have been constructed since 2000, with 99,000 (around 44% of total new family housing) built in 2007 (AMA, 2009b) and more than 250 apartment blocks located in Manchester city alone (Paradisewharf, 2010). The BRE (2004) survey on heating options for flats showed that the four most common types of flats and apartments in the UK are; conversions, low rise, high rise or tenement[1] flats.

Energy used by the domestic sector contributed to around 29% (see Figure 1) of the overall UK energy use in 2011 (DECC, 2012b) with overall inner city domestic electricity demand being only 5% in 2005 (Figure 2).

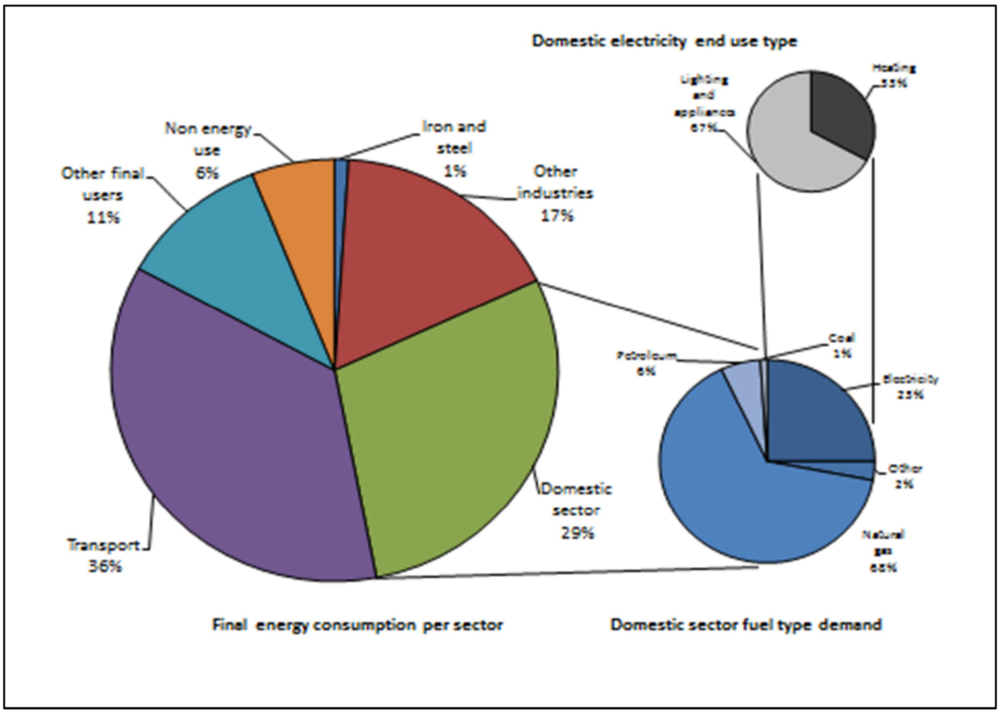


Figure 1 Final energy consumption sector analysis (DECC, 2013b; ECUK, 2013).

Heat electrification trends are however changing this balance especially as electricity as a source of fuel is growing in popularity. Electric systems now account for around 12% of the total UK domestic heating market (AMA, 2009a), reflecting the growth in the number of flats and apartments. Of the electricity consumed by the domestic sector in

[1] Tenement flats – typically pre – 1919 construction with solid walls (BRE 2004. Comparison of running costs for different heating options in hard to treat flats. London: Building Research Establishment for Energy Saving Trust.)

2011, 21% was reputed as being purchased under some form of off-peak pricing structure (DECC, 2013b). Government energy policies and initiatives recognise the growth of electricity use in cities and the need for the decarbonisation of generation – this is explored further below.

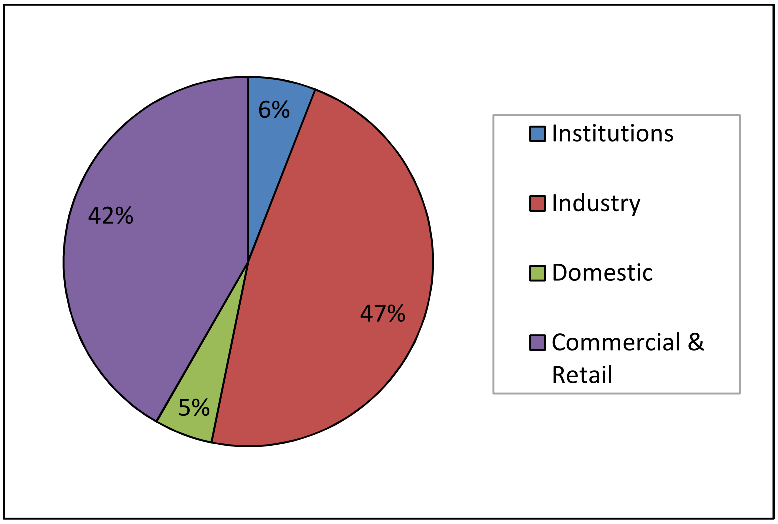


Figure 2 Inner city electrical demand (Wiltshire, 2005).

2.1.2.2 Policies

The UK has committed to cutting greenhouse gas emissions by 80% over 1990 levels by 2050 (OPSI, 2008), and to provide 15% of its energy from renewable resources by 2020 (EU, 2009). However, just 6% of electricity came from renewables in 2009 when CO_2 emissions were 175 million tonnes from total generation (DECC, 2010b). The latest energy white paper, the UK Low Carbon Transition Plan (LCTP) for 2020, (DECC, 2009c) describes a significant implication of the proposals as the increase in the provision of energy services through the electricity network, including electrified heat provision to homes particularly through the use of heat pumps (ICEPT and CES, 2010).

Space and water heating, and increasingly space cooling (Day et al., 2009), are significant sources of energy demand in the UK (DECC, 2010b). In 2008 heat generated from renewable sources accounted for only around 1% of total residential heat demand; this would need to increase in order to meet EU targets (EU, 2009). To achieve the 2020 target of 15% of energy supplied by renewables, new ways need to be developed to stimulate demand for energy from renewables. The UK Government therefore published the Renewable Energy Strategy (RES) (DECC, 2009d) in 2009 which describes the UK's climate change programme and explains how this legally binding target will be met (OFGEM, 2010b). The strategy gives attention to the decarbonising of electricity, the provision of new heat sources including biogas and creates opportunities for individuals and communities to harness renewable energy. The first Renewable Obligation Order (ROO) came into force in April 2002 as the main support scheme for renewable electricity projects and is designed to provide incentives to the energy sector for renewable generation. The orders place an obligation on licensed electricity suppliers in England and Wales, Scotland and Northern Ireland to source an increasing proportion of electricity from renewable sources (OFGEM, 2010b). Suppliers meet their obligations by presenting sufficient Renewable Obligation Certificates (ROCs) to cover their obligations - in 2008/09 it was 9.1 per cent of electricity from renewable sources in England, Wales and Scotland (OFGEM, 2010b). Furthermore, financial incentives in the form of the Renewable Heat Incentive (RHI) have also been introduced, as part of RES. The RHI involves payments for generating heat from renewable energy with eligible renewable heat sources and technologies including: solar thermal, biomass, heat pumps and biogas (NERA, 2009).

In addition to these, thermal efficiency of existing and new housing is one of the factors that could help reduce energy demand in the residential sector – the next section explores current planning requirements to reduce energy demand and decarbonise energy in urban dwellings.

2.1.2.3 Planning

Housing forms a significant portion in the UK’s emissions profile (CaLG, 2007a) and with this in mind, the Department for Communities and Local Government (DCLG) published its blueprint for new housing over a 15 year period (CaLG, 2007d). Within this, the Code for Sustainable Homes (CSH) provides a roadmap towards all new homes being *zerocarbon* by 2016 (Dimplex, 2009). The aim of the CSH, is to improve the overall sustainability of new homes by setting a single national standard for England, Wales and Northern Ireland (CaLG, 2009) and is a major driver for housing associations and other key bodies such as English Partnerships and City Councils. With existing and proposed improved building and insulation standards required for new homes, local authorities are now required to focus on existing homes as a way to achieving national carbon budgets (ConsumerFocus, 2009).

Local authority (LA) planning statements should reflect central guidance on climate change and renewables for new developments (CaLG, 2007d). Planning requirements including: Planning Policy Statement 1 (PPS1) (ODPM, 2005) and Planning Policy Statement 22 (PPS22) (ODPM, 2004c) cover the delivery of sustainable development and renewable energy targets and are enacted within Supplementary Planning Documents (SPDs) and Local Development Frameworks (LDFs). These policies show a tightening of planning standards for new and existing homes however, local authorities often differ in their interpretation of current policies on renewable energy, ranging from having no formal requirements to requiring 20% renewable energy (e.g. Manchester) (Quantum, 2008).

2.1.2.4 Regulations

The Building Regulations and Building Codes are a set of requirements laid down by Parliament to ensure that building work is carried out to approved standards including the conservation of fuel and energy within buildings (ODPM, 2006a). These regulations required greater thermal efficiencies by 2013 and set the standards needed for ‘zero carbon’ buildings in 2016 (CaLG, 2007a). As part of these regulations, approved documents *‘Part L1a and L1b’* (ODPM, 2006a; ODPM, 2006c) provide guidance for new and existing buildings regarding reducing carbon emissions; not just through targeting heating appliances but through the way the building functions as a whole (and includes insulation and ventilation). Furthermore, document *L1a* stipulates that the energy performance of dwellings and the annual CO_2 emissions from a dwelling should be calculated using the Standard Assessment Procedure (SAP) 2009 (DECC, 2009c).

The following regulations have also been put in place to enhance the uptake of energy efficiency, micro-generation and safe energy utilisation; these have been initiated by the government and other regulatory bodies:

- The Carbon Emissions Reduction Target (CERT) came into effect in April 2008, obliging electricity and gas suppliers in Great Britain to help reduce carbon dioxide (CO_2) emissions from homes (CERT, 2009). Electricity and gas suppliers are now obliged to promote initiatives that improve energy efficiency and increase the amount of energy generated from renewable technologies such as; wind turbines, solar panels and ground source heat pumps (EST, 2010). Suppliers meet this target by promoting the uptake of low carbon energy solutions to household energy consumers, thereby assisting them to reduce the carbon footprint of their homes. Furthermore, the *Green Deal* is a government proposed initiative to increase the energy efficiency of properties both in the public and private sectors. The cost of initiatives such as double glazing and insulation are recovered through instalments on the household's energy bills (DECC, 2011c).

- The Household Energy Management Strategy (DECC, 2010d) sets out government plans to support homeowners and tenants who want to save energy in their home or generate their own clean energy. Part of the strategy to stimulate the uptake of micro-generation includes feed in tariffs (FITs). This scheme was introduced in April 2010 to encourage the deployment of additional small-scale (less than 5MW) low-carbon electricity generation. In addition to payments for exported electricity to the grid, a guaranteed payment is received from an electricity supplier of their choice for the electricity they generate and use (DECC, 2011b).
- Because of the trend towards building more multi-occupancy dwellings (CORGI, 2007), the guideline IGE/G/5 was published in 2006 to address several complex technical and legal issues that arise with the inclusion of gas pipes, meters, common pipe work and appliances in buildings that contain multiple individual dwellings (IGEM, 2006). The guidelines are intended to improve safety levels for gas installations in multi-occupancy buildings through rigorous construction standards and procedures.
- SAP – the Standard Assessment Procedure rates the thermal efficiency of a dwelling and is based on estimated space and water heating costs. A rating of 100 indicates an extremely efficient house. SAP can provide both home buyer and renters with an indication of the properties energy efficiency and assist them in making an informed decision about the property.

2.1.2.5 Energy security

Security of energy supply has recently re-emerged as a focus of government policy intervention (Turton and Barreto, 2006) for many countries including the UK. This section describes the energy security drivers for the electrification of heat.

The UK faces a number of energy security of supply challenges including the increasing reliance on imports of oil and gas and the need of investment in gas infrastructure, power stations and electricity (BERR, 2007b). The reliance on natural gas as a major primary fuel, coupled with declining UK fossil fuel resources and a reduction in electricity generating capacity from other domestic sources suggests the need for diversity and a balanced mix in order to provide security of supply (Hodgson, 2004). Security of supply encompasses both the availability and the reliability of gas supplies and is a measure of the degree to which an uninterrupted supply of gas can be maintained (HoP, 2004). By increasing the diversity of gas suppliers and supply routes, security of supply can be improved, reducing vulnerability to disruption and the threats to gas supplies (HoP, 2004). Around three quarters of the UK's heat comes from gas fed through the nationwide network (DTI, 2006b) so that new pipelines, LNG terminals and gas storage facilities are required and some are currently under construction (HoP, 2004). Energy security is a key driver in changing this centralised model to one of enhancing micro-generation and decentralising heat and power provision through a combination of new and existing technologies. Decentralising makes it possible to generate energy efficiently near to where it is to be used potentially delivering lower emissions, increased diversity of supply and in some cases lower cost (DTI, 2006b).

2.1.2.6 Energy poverty

Investment costs are often a barrier to incorporating low carbon technologies into new developments. At the same time, the cost to the consumer of fossil-based energy is rising (Quantum, 2008). Increases over the last seven years have shown electricity and gas average duel fuel retail bills for standard a domestic customer increasing 216% from £600 in 2004 to £1,294 in 2011 (OFGEM, 2011; Energywatch, 2011). Continued uncertainty about energy price rises is gradually driving developers to consider installing renewable energy technologies because they want to be able to "take control over future costs" (Quantum, 2008).

Reducing energy demand plays a key role in any secure, low-carbon future (EEA, 2008). However, if demand reduction takes place as a response to higher prices, the welfare implications could be significant (UKERC, 2009b). Very young children and people above 40 years can especially be affected health wise through fuel poverty and poor quality housing. Cold and damp can ignite or exacerbate physical illness in fuel poor households - in addition, the mental health of householders can be significantly affected (OECD/IEA, 2011).

Fuel poverty affects about 2.3 million households in England (Moore, 2005) and with increasing energy costs, this figure is projected to rise. Fuel poverty is particularly evident within urban areas (i.e. Figure 3). A household is currently classified as being fuel poor if a fuel bill in excess of 10% of income is required to maintain adequate domestic thermal comfort in winter (Hong et al., 2009). The *Hills Review* is considering fuel poverty management and is suggesting a new definition of fuel poverty as *low income/high costs*. This takes into consideration housing costs and household size along with other expenditures and therefore better reflects household resources (Hills, 2011). However, fuel poverty is complex, Boardman (2012) suggests that the energy inefficiency of the home is the real cause of fuel poverty. There needs to be a recognition of the difference between the symptoms which result in low daily household expenditure on fuel and the cause of fuel poverty – the failure to invest in capital to improve energy efficiency (Boardman, 2012). Policies that target the fuel poor are difficult – requiring both social and environmental factors but Boardman (2012) indicates that demand reduction is better than new forms of energy supply.

The Warm Homes and Energy Conservation Act (2000) (HMGovernment, 2000) requires the Government to ensure that, as far as reasonably practicable, people do not live in fuel poverty (NAO, 2009). As a result, the Government developed a strategy that aimed to eliminate fuel poverty by 2010 among vulnerable households (DTI, 2001), nevertheless, it recognised that poor energy efficiency in dwellings is one of the main causes of fuel poverty (Hong et al., 2009), and focused on the introduction of energy efficient grants through the *Warm Front* scheme. The scheme targeted low income households living in the private sector by providing funds for insulation, efficient heating systems and draught proofing (NAO, 2009). Interim conclusions suggested that

the Governments current and future policies in relation to fuel poverty are not sufficient to meet stated targets due to the cuts in the *Warm Front* programme funding and the need to spend more on energy efficiency measures (Boardman, 2008).
However, the *Warm Front scheme* finished during 2012 and a consultation process as to its replacement is in progress (DECC, 2011a). The English house condition survey (EHCS) (CaLG, 2007c) carried out in 2007 stated that over 3,423,000 homes failed the decent homes standard due to poor thermal comfort, this consisted of nearly 3 million of private tenure and the rest social tenure.

Support for public housing came through the Government's Neighbourhood Renewal Fund (NRF) set up in 2001 to enable the 88 most deprived local authorities in England to improve services and narrow the gap between the most deprived areas and the rest of the country. The decent home standard was part of the support to these areas and brought about improvements to homes through better insulation and more efficient heating systems (CSMHT, 2010). The poor performance and high operational costs of electric and oil heating systems has been recognised as a key contributory factor toward fuel poverty (Government, 2008).

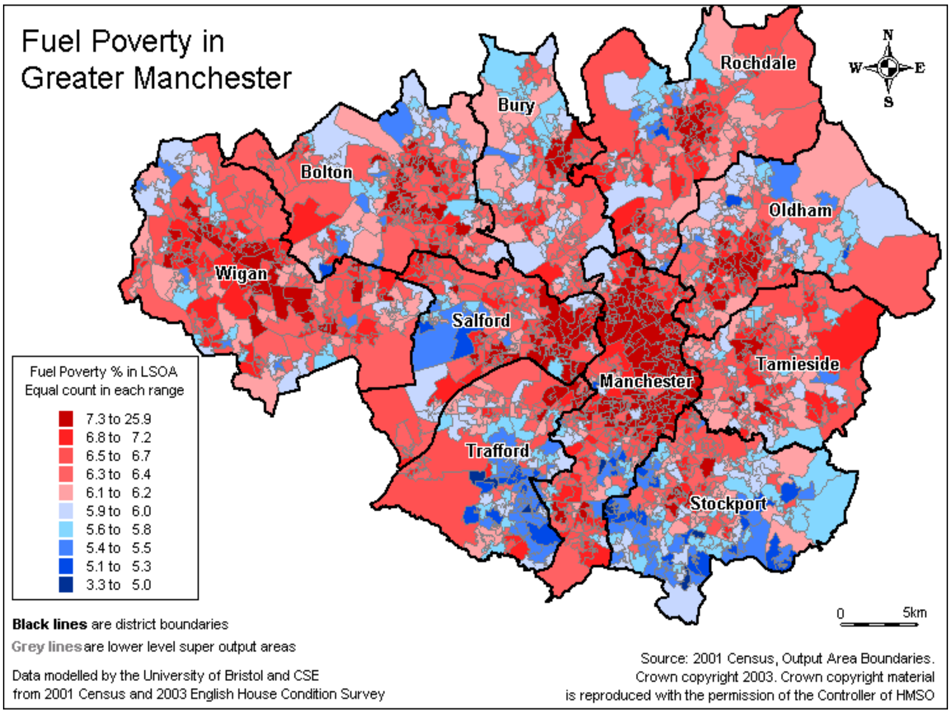


Figure 3 Fuel poverty indicator for Greater Manchester (Energy, 2010a).

[Red indicates a higher % of fuel poverty in the specified geographical area (LSOA)].

2.1.3 Implications of the electrification of heat on energy supply in cities

2.1.3.1 Existing energy supply and generation

The existing energy system in the UK is predominantly reliant on fossil and nuclear fuels. Energy production and consumption by primary fuel is shown in Figure 4 (DECC, 2010b). Although the UK presently exports gas to the Netherlands, Belgium and Ireland, it has been a net importer since 2004 and is now dependent on fuel imports to sustain energy demand (Asif and Muneer, 2007; HoP, 2004). The UK electricity system is reliant on a small number of large-scale centralised power plants (DECC, 2010b) fuelled by natural gas, coal or nuclear fuel with oil taking an emergency support role (Figure 5) (Econnect, 2006). A small proportion (7.0%) is derived from large scale renewables such as wind, tidal wave, hydropower, biomass, solar or geothermal (CAT, 2010; DECC, 2010b).

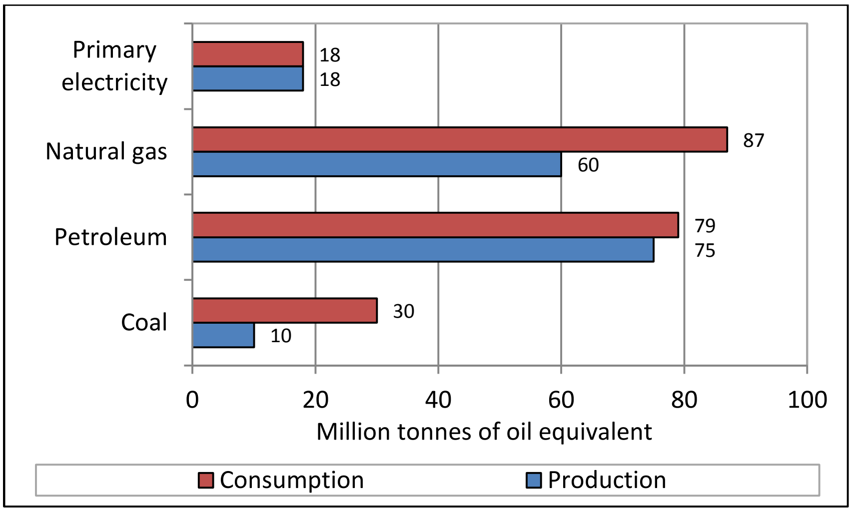


Figure 4 Production and consumption of primary fuels in the UK in 2009 (DECC, 2010b).

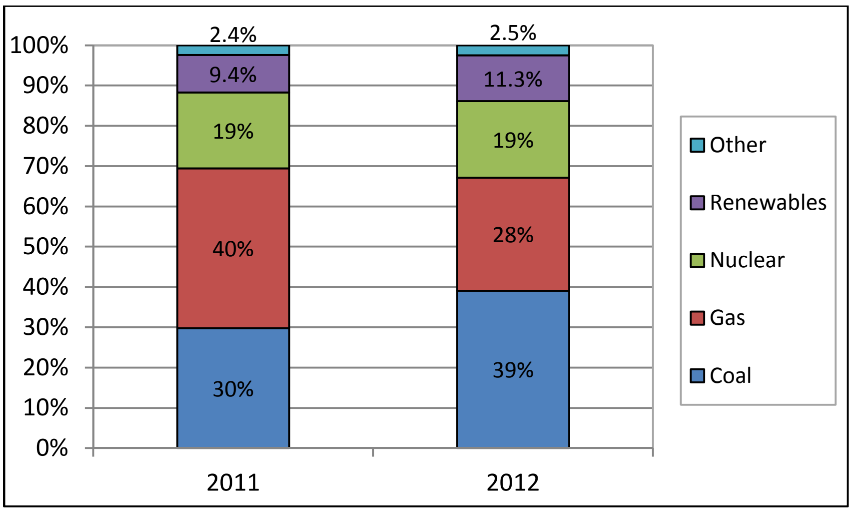


Figure 5 Shares of net electricity supplied, by fuel input in 2011 and 2012 (DECC, 2013b).

With respect to heat supply in the UK, the majority is still supplied by natural gas but, as already mentioned, the share of electric heat is growing. Provision of heat from electricity is about 30% less efficient overall and therefore has a higher impact on the environment than heat from the combustion of natural gas (EAESL, 2010); it is also generally more expensive. However, the higher end-use effectiveness of electricity in space and water heating (nearly 100% at point of use) (Bodansky, 1984) largely, but not completely, compensates for the loss of energy at the generating plant. Combined with the simplicity of use and improved safety compared to gas heating, this provides significant advantages for the shift to electric heating. A switch to electric heating would also mean displacing the environmental impacts from cities (from the combustion of natural gas) to rural areas where power plants are normally situated (Luickx et al., 2008). Therefore, the switch to the electrification of heat could cause a shift in environmental, economic and social impacts (Caldecott, 2009; ENSG, 2009; SKM, 2008); it was not clear whether this change is more or less sustainable than current gas systems, hence the motivation for this research.

2.1.4 Sustainability of heating technologies

2.1.4.1 Introduction

Although demand for electricity for space and water heating is growing, gas is currently the principle source of heat (ICEPT and CES, 2010) (Figure 6). Gas, however may not be the best option on efficiency grounds since energy efficiency improvements and regulations offer lower space heat demand that can often be satisfied by smaller electric heating systems rather than larger gas boilers (ECI, 2007). Electric space heating, however, produces 1 tonne more CO_2 per 60 m^2 floor area per year compared to a condensing gas boiler (Olivier, 2007).

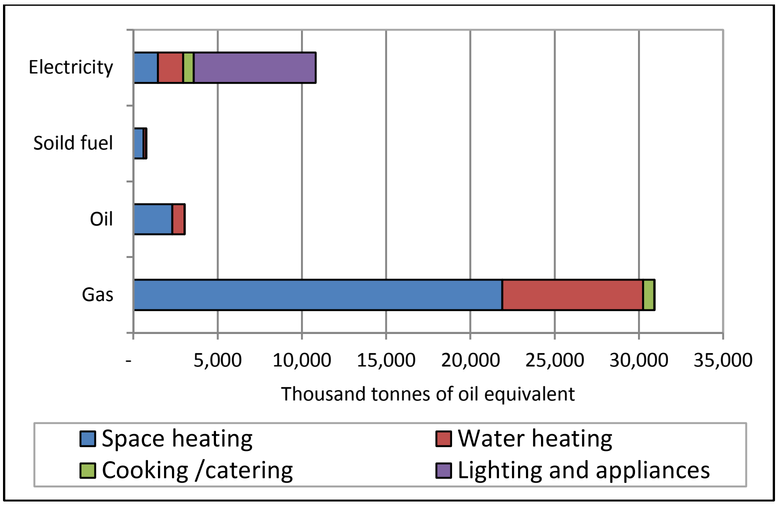


Figure 6 Domestic energy consumption of heat by fuel in 2008 (DECC, 2010b).

A number of countries; such as France, Germany and the British crown dependencies of Jersey and Guernsey, have positively promoted electric heating for homes. Luickx et al (2008) describe the impacts on GHG emissions of a massive introduction of electric heating (both heat pumps and resistance heating) into France, Germany, Belgium and Netherlands. They conclude that based on the French generating mix, the GHG emissions would be reduced due to its reliance on nuclear power (GC, 2008). However, replacing fossil fuelled heating by heat pumps in Germany results in an increase in GHG emissions and the same is true for the Netherlands. The islands of Jersey and Guernsey are presently supplied with electricity from France taking advantage of nuclear electricity and lower costs and emissions compared to that of heating using imported gas (JEC, 2010).

In the UK, electric space and water heating in the development of new flats in major cities has been an option for several years (Olivier, 2007), usually in cases where there was no original gas supply (e.g. warehouse conversions) or where there was no access to mains gas. Building developers often point to a number of advantages of an ‘all electric’ building compared to other supply options; low capital costs for installation, low maintenance costs over the lifetime of the heating system, safety and no landlord inspection or servicing regulations (Olivier, 2007).

As mentioned above, domestic energy accounts for a large proportion of total national energy consumption and carbon emissions. Many heating system types are available that provide space and water heating to dwellings, with a range of fuels and characteristics (Henderson and Young, 2008). However, assuming a typical life of these systems (around 10-20 years) then it can be assumed that between now and 2050 most heating systems within buildings in the UK will need to be replaced at least twice (Energy, 2008).

Realistic ways to efficiently heat spaces and water were explored by Miller (2005) who found that electric resistance heating produced by a coal fired plant was the most wasteful and expensive. Technologies with the greatest potential to reduce future carbon emissions the environmental performance were assessed by Henderson and Young (2008) and adopted by SAP (BRE, 2005a): for example gas boilers and electrical resistance heating. Natural gas has a high net energy ratio (NER)[2] reflecting its relative availability and lower cost of extraction, whilst electricity generated from gas or coal, and using resistance heating, exhibits a much lower NER with passive solar exhibiting the highest (Figure 7). The lowest net energy efficiency (NEE)[3] is obtained through the use of electricity resistance heating with electricity produced from coal fired plants (Figure 8) and significant energy losses during electricity generation and distribution. The highest NEE is exhibited by a super insulated house.

Fuel factors are used in the UK building regulations and demonstrate the ratio of the CO_2 emission factor (kg CO_2 per kWh) for a given fuel to that of mains gas, the primary heating fuel in the UK. The fuel factor means that if the chosen heating fuel is more carbon intensive than gas, the Target Emission Rate (TER) is adjusted for dwellings that are off the gas grid or in blocks of flats where a gas service to each apartment is not a preferred choice. These regulations are different according to energy type and require increased home building standards including higher levels of insulation to reflect the level of designed efficiency - this provides fuel factors of 1.47 for electricity compared to 1.00 for gas (Brinkley, 2010). Since new buildings can be built to require almost no

[2] Net energy ratio (NER) determines high quality usable energy available where a higher NER refers to greater net energy availability. Net energy can be defined as the amount of high quality usable energy available from a resource after subtracting the energy needed to make it available, MILLER, G. T. 2005. *Living in the environment,* CA, Thomson.

[3] Net energy efficiency (NEE) describes how much useful energy we get from an energy resource after subtracting the energy used and wasted in making it available ibid.

winter heating (Harvey, 2006), it is expected that the scope for the effective use of larger individual heating systems in future high-performance buildings will decline.

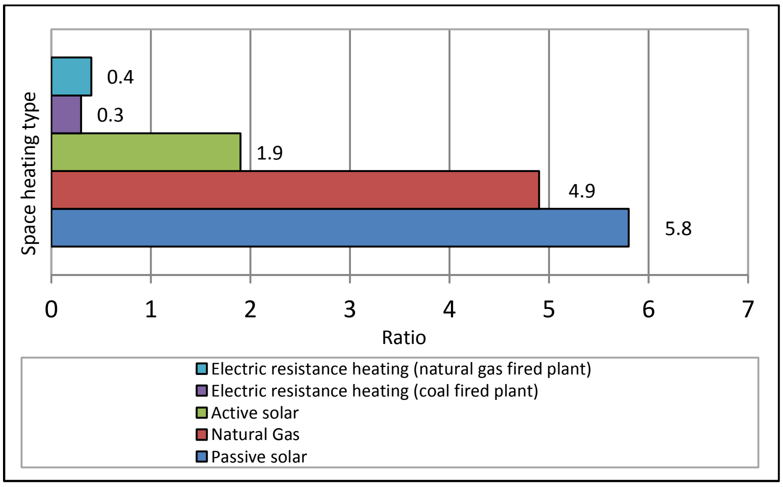


Figure 7 Net energy ratios of different energy types and associated systems over their lifetimes (Miller, 2005).

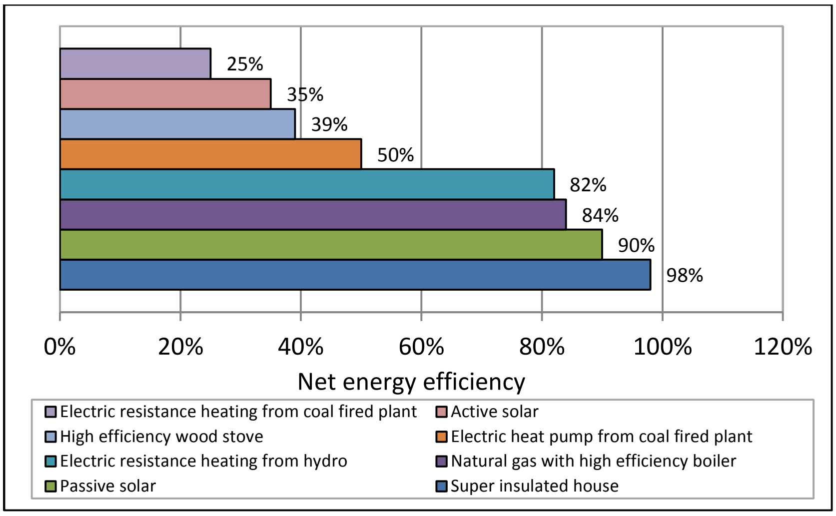


Figure 8 Ranking of efficiencies for heating an enclosed space (Miller, 2005).

There are relatively few renewable energy systems that are considered suitable for wide scale installation and utilisation in urban dwellings due to the requirements for a large roof area or ground space which are unlikely to be found in most flats or apartments (Henderson and Young, 2008). However, a trend has been seen in Manchester and other cities where PV and wind generators have been installed and are playing a key role in energy supply (Building, 2005) through providing useful energy in terms of heat or electricity for common space lighting, heat for central hot water storage or feed in electricity to the grid. However, it is whether gas, electricity and heat are already available in the building for these retrofit projects that generally determines what the final heating technology will be (CSMHT, 2010).

The following section focuses on the feasibility of current individual and communal technologies and systems that are used for apartment blocks including electric resistance heating, gas boilers, district heating, solar thermal, and heat pumps - see Table 1 for an overview (ElementEnergy, 2008; EST, 2006a). The review considers environmental and techno-economic sustainability of the technologies as reflected within current literature.

Table 1 Space and water heating and cooking technologies appropriate for urban dwellings *(ElementEnergy, 2008; EST, 2006a).*

Technology	**Energy source**	**Renewable/ High carbon/ Low carbon**	**Energy produced**
Resistance heating: - storage heaters - panel heaters - underfloor heating - immersion heaters - electric boiler/warm air.	Electricity.	Currently high carbon due to the UK electricity supply mix.	Heat for space and water.
Heat pumps: - air source - ground source.	Electricity and thermal energy from either air of ground.	Currently high carbon due to the UK electricity supply mix but fuel factors planned to be adjusted to match that of natural gas (CaLG, 2007b).	Heat for space and water.
Gas boilers: - gas combination - gas condensing.	Natural gas.	Low carbon compared to electricity.	Heat for space and water usually via a wet system including radiators.
District heating: - heat pipes and radiators - apartment block based heating system.	Range of fuels: gas, MSW, biomass.	Renewable/Low carbon.	Heat for space and water usually via a wet system including radiators.
Combined heat and power: - heat pipes and radiators - apartment block based heating system.	Natural gas, biomass, MSW.	Renewable/Low carbon.	Heat for space and water usually via a wet system including radiators. Electricity for export or local distribution.
Solar thermal: - individual - community.	Solar energy.	Renewable.	Heat for water.
Cooking technologies: - electric hobs and ovens - gas hobs and ovens.	Electricity, natural gas.	Currently high carbon for electricity.	Heat for cooking.

2.1.4.2 Resistance electric heating

2.1.4.2.1 Description of resistance electric heating

The electric heating option is currently used by a growing number of city centre residential developments, and rural homes located away from the natural gas network. However the high environmental impacts of using electricity as the main residential space and water heating fuel are well documented in literature (Thyholt and Hestnes, 2008; Torekov, 2007; Shah et al., 2008; Olivier, 2007). Electric resistance heating operates by the passing of an electric current through a resistance such as a coil, wire, or other obstacle which impedes current and causes it to give off heat. Electric resistance heating is a proven and established technology that is effectively used in the UK and abroad (JEC, 2009). Heating technologies that operate solely on electricity and are used for the primary resistance heating requirements of homes are:

- Electric resistance storage heaters including integrated storage/direct systems;
- Electric resistance panel heaters;
- Electrical underfloor heating;
- Immersion heaters;
- Electric boilers serving central heating systems; and
- Electric warm air systems.

A typical installation consists of a series of electric storage or panel heaters placed and wired into the electricity supply within each room. Water heating by electricity consists of electric immersion heaters that are placed into a water storage cylinder tank and controlled by a programmable unit and thermostats placed on the cylinder. Where electric resistance heating is installed higher rating cables and systems are required within the house and network (WPD, 2004). The features of the three main electric heating technologies are described below.

- *Electric resistance storage heaters* - utilise electricity through a series of elements to heat a storage medium, usually bricks (Dimplex, 2010). Storage heaters give out heat in two ways: through radiation from the front panel, and by convection heat in the form of warm air (Foundation, 2010). The heat is slowly released from the thermal store (the bricks) as required during the day and evening. Usually each room to be heated has one or more storage heaters with a charge and temperature control (CaLG, 2008a) and designed to take advantage of the off-peak electricity tariffs. Storage heaters are principally made from steel sheet, insulation material, thermal bricks and elements made from copper or *Incoloy* alloy (nickel-iron-chromium). Users often find that in the middle of winter they still need to supplement the storage heating by a direct electric heater, such as a fan heater (Foundation, 2010). Many users do not fully understand the controls and education programmes are in operation to improve user understanding and system operation (CSMHT, 2010).

- *Electric panel heaters* - are the most popular electric space heating technology for new apartment block developments (Bradwell, 2010) and utilise standard rate electricity through a series of heating elements to heat a room (BRE, 2003). Panels are manufactured from the similar materials as storage heaters except bricks are not utilised. Such heaters have a local time and temperature control (CaLG, 2008a) and more sophisticated systems are available to improve the heat management of individual rooms. In general, this form of heating is more expensive to run than gas boilers since they are unable to take full advantage of off-peak tariffs (BRE, 2003).
- *Underfloor heating* - works in much the same way as storage heaters, except that there are fewer controls possible. In most cases the electric heating element is laid in the floor at the time the house (or flat) is built, and concrete is poured around the heating elements to provide the thermal mass instead of the heat retaining bricks. The main advantage of this type of heating is the lack of radiators or storage heaters on any walls (Foundation, 2010).

2.1.4.2.2 Environmental sustainability of electric heating

The environmental sustainability of electric heating found in literature has typically considered GHG emissions, primary energy consumption and energy and emission payback times. For example, the LCA study of electric heaters compared to gas boilers suggested that, primary energy consumed by using a gas boiler is lower than using an electric heater (Ferreira, 2007); however the efficiency at the point of use is much higher in the case of electric heaters where nearly 100% of energy supplied can be changed to heat. A study by BRE (2003) summarised in Table 2, demonstrated that CO_2 emissions from electricity for heating are nearly double those from using natural gas in a condensing boiler.

Table 2 CO_2 emissions (tonnes/year) for heating in two property types (BRE, 2003).

Dwelling type:	**Flat**		**Semi-detached**	
Fuel type	***Existing***	***New***	***Existing***	***New***
Electricity – standard tariff	3.83	1.78	5.92	2.79
Electricity – off peak	3.83	1.78	5.92	2.79
Gas boiler – condensing	2.0	0.93	3.09	1.46

Most studies have identified as indicated previously that the operational stage is generally the largest contributor to the environmental impacts with over 99% of the life cycle environmental impact generated in this phase (Ferreira, 2007). No studies have considered the manufacturing and disposal impacts of electric resistance heating equipment however these life cycle stages have been considered in this work, and are discussed later in the report.

2.1.4.2.3 Economic sustainability of electric heating

In order for electric heating to be economical and to meet the increasingly strict regulations for home space heating either major improvements must be made to the insulation of the building fabric (which affects the building construction process and costs) to reduce heating demand (BRE, 2003; IEA, 2010b), or use must be made of cheaper electricity rates via Economy 7 or Economy 10 (UKpower, 2010). As an example of the operating costs in existing and new buildings, Table 3 compares the costs of space and water heating by electricity and gas (BRE, 2004; DTI, 2001; NAO, 2009); and shows that the cost of using electric resistance heating on standard tariff is nearly five times more expensive than using natural gas.

Table 3 Annual fuel costs for heating and hot water in different property types (BRE, 2003).

Home type:	**Flat**		**Semi-detached**	
Fuel type	***Existing***	***New***	***Existing***	***New***
Electricity – standard tariff	£656	£214	£1013	£365
Electricity – off peak	£264	£86	£408	£135
Gas boiler – new condensing	£138	£45	£214	£71

Over 6 million homes in the UK presently have an economy 7 meter, providing 7 hours of cheaper electricity generally during the night (BBC, 2009). The economy 10 scheme is more flexible and permits 10 hours of cheaper off-peak electricity with 3 hours in the afternoon, 2 hours in the evening and 5 hours overnight (UKpower, 2010).

2.1.4.3 Heat pumps

2.1.4.3.1 Description of heat pumps

There are currently three types of heat pumps available: air source (ASHP), ground source (GSHPA) and water source (WSHP) (EST, 2006b). In the context of city centres and residential apartment blocks the latter two pumps are presently considered less feasible for large scale heat provision mainly due to ground area or water course availability restrictions (BRE, 2004) and therefore will not be detailed within the current literature review.

Air source heat pumps extract heat energy from the air and use this for space heating with the pump consuming electricity from the national grid (Mackay, 2008). ASHP use a fan to draw in external air over an evaporator containing a refrigerant such as R-134a or R-744 where the heat is extracted from the air (Carrier, 2010). The extracted heat can either be circulated to the required space using another fan or transferred to water for circulation through a wet heating system (Bertsch and Groll, 2008). The wet heating system requires larger radiator areas for the same heat demand due to the lower water temperature (GSHPA, 2010). ASHP require sufficient surrounding external space to allow air to circulate and an external wall or similar structure for the ASHP to be fitted securely.

The efficiency of a heat pump is measured by the Coefficient of Performance (CoP) which describes the ratio of useful heat movement to work input and for a typical ASHP; this ranges from 2.5 – 2.8 seasonal variation (Carrier, 2010).

2.1.4.3.2 Environmental sustainability of heat pumps

Environmental sustainability studies of heat pumps consider the GHG as a measure of sustainability and primary energy comparisons for their efficiency. In the USA heat pumps have varying environmental impacts depending on the source of primary electricity with lowest impacts experienced in states with higher renewable electricity generation (Shah et al., 2008). Compassions of different heating options show that the ASHP when combined with solar water heating (SWH) produces 28 kg CO_2/m^2/year being more carbon intense than a gas boiler but producing only 65% of CO_2 from electric panels with SWH (Henderson and Young, 2008).

Heat pumps exhibit the characteristic of losing efficiency during periods of extreme cold or heat due to the temperature differential, resulting in greater energy usage. A study of pilot ASHPs in the UK showed that before improvements, households emitted on average 11.7 tonnes of carbon per year but with air source heat pumps installed this was reduced to 4.9 tonnes (Government, 2008). In line with electric resistance heating, the operational stage of the ASHP is the largest contributor to environmental impacts (Mustafa Omer, 2008) again due to the high carbon mix of electricity currently in the UK.

Refrigerant emissions such as chlorinated hydrocarbons during use and maintenance can contribute to environmental GWP (Saner et al., 2010). The manufacturing of the air source units also creates environmental impacts through the use of materials such as steel, copper, aluminium and electronic components (Saner et al., 2010).

Improvements to the environmental sustainability of ASHP mainly focus on the form of the primary energy mix and moving this ultimately toward renewable generation (Shah et al., 2008). Manufacturers are trying to improve the CoP of ASHP with some exceptional models providing up to 6.0 CoP (Levine et al., 2007). With ASHP requiring electricity for their operation and extensive installation needs – it is not currently clear how sustainable such systems can be compared to current technologies in the context of cities, hence a focus for this study.

2.1.4.3.3 Economic sustainability of heat pumps

Air source heat pumps consume less electricity for the same heat output compared to resistance electric heating (Torekov, 2007) resulting in a lower overall cost. Pilot programmes in Scotland give an average cost for an ASHP as £10,500 fully installed with a potential to reduce this to £9,000 with bulk installations (Government, 2008). ASHP were found to provide the greatest overall value for money in terms of households lifted from fuel poverty per £1m capital spend; lifting 43 households from fuel poverty as opposed to 37 households for electric resistance heating (Government, 2008).

2.1.4.4 Gas heating

2.1.4.4.1 Description of gas boiler heating

Domestic heat demand represents 85% of total domestic energy use with the majority of this heat being delivered by gas through gas boilers using a central heating system (ICEPT and CES, 2010) and with recognition that in the past, gas central heating has played an important role in improving residential temperatures (Shorrock, 2008).

A typical heating system comprises a gas boiler, water storage tank (when required), hot water pipe work system (including pump and valves), a series of heat emitters (radiators or pipes) and a control system. Other means of heating homes by gas include gas fires; gas heaters; and micro CHP. The size of the installed gas boiler is dictated by the output required and this is measured in terms of number of radiators and hot water cylinders, however most boilers installed before 1989 were up to 30% oversized due to a trend to oversize them to ensure that homes are adequately heated. The range of gas boilers currently available and described by Hill (2010) include:

- *Condensing boilers* - providing heating for hot water storage and space heating. These boilers are now typically installed in houses and maximise efficiency through cooler water returning from the radiators being passed through a secondary heat exchanger to be warmed by the hot flue gases which would have been expelled into the air in older style boilers. The warmer water is then sent back to the radiators. Condensing boilers recover and recycle wasted heat enabling them to operate up to 95 to 97% efficiency (Sedbuk, 2010);
- *Combination (Combi-type) boilers* - heat water for the central heating in the same way as condensing boilers but also provide instant hot water and eliminate the need for water storage and supply tanks. Modern combi-boilers have efficiencies of between 80 and 84% (Sedbuk, 2010). Although combination condensing boilers are the UK’s bestselling boiler, accounting for around 70% of sales, there is increasing awareness of their limitations, particularly concerning the low hot water flow rates especially when demand is high (AMA, 2009a);
- *Old style conventional boilers* - rely on gas jets that play on a cast iron heat exchanger through which water passes to be heated and require both supply and

hot water storage tanks. These (older) boilers had lower efficiencies of between 60 and 70% (Heatandplumb, 2010);

- *System gas boilers* - have auxiliary components built into the boiler including pump, expansion vessel, safety valves and programmer; and
- *Back boilers* - consist of a built in boiler with a gas fire front and open flue.

In the UK, gas boilers must have an efficiency rating of SEDBUK A or B which equates to 86% or above in efficiency terms. Non-condensing boilers have a lower efficiency at part load than full load (Roberts, 2008) whereas modern condensing boilers have constant or even higher efficiencies at part load, down to only 10–30% of their full load.

Concerning manufacturing and design of boilers - the recent *Ecodesign Directive* (ED) provides EU wide rules and guidance for improving the environmental performance of energy related products (ERPs) including boilers and impacts on all new designs and manufacturing methods (Farnell, 2010).

Safety can be an issue with gas boilers. In larger heating schemes serving many households such as a centralised network for apartment blocks, larger more complicated condensing gas boilers are typically used (MHS, 2010), although those constructed prior to 2000 typically had individual installations. However, in low rise buildings (i.e. up to 3 storeys high) and in new developments or conversions, gas heating through individual boilers continues to be installed (CORGI, 2007). Surveys carried out on people living in these buildings (Croxford, 2006) suggest that significant safety issues exist with gas fires which are the appliance most likely to be considered by *Health and Safety Executive* as dangerous (26% of all gas fires), followed by cookers (7%), with gas boilers the least likely to be unsafe - only (5%). Obligations are placed on gas engineers, landlords and consumers to ensure that gas appliances are operating safely, landlords for example must arrange for a gas safety check to be carried out every 12 months by a Gas Safe Registered Engineer (gassaferegister, 2011; HSE, 2010).

2.1.4.4.2 Environmental sustainability of gas boiler heating

The environmental sustainability of gas boiler heating is typically determined in the published literature by comparing their GHG emission, primary energy consumption, energy and emission payback times with alternative heating systems such as heat pumps and district type heating. Environmental impacts assessed by Ferreira (2007) and Sasnauskaite et al (2007) show that over 99% of the life cycle environmental impact is in the operational phase. At the individual boiler level, Shah et al (2008) identifies a gas boiler as having the highest impact in all the damage categories compared to a heat pump and gas warm air furnace. Sasnauskaite et al (2007) identifies that steel radiators as part of the heating system have the largest influence in the production phase and this aspect therefore applies to any such system utilising radiators. Riva et al (2006) determined that natural gas is environmentally better than other fossil fuels in the final use stage, and achieves even better results if complete fuel cycles - from production to final consumption - are taken into account. However, detailed environmental impact studies based on gas boilers and their associated systems are not represented in literature but have been considered in this work and are discussed later in the report.

2.1.4.4.3 Economic sustainability of gas boiler heating

The gas boiler heating is currently the most economically competitive and popular option for central heating when compared to electricity, oil and solid fuels (Henderson and Young, 2008). Typical costs for heating flats and semi-detached homes using old and new gas boilers are shown in Table 4. Although there is a wide variation in individual cases due to climate, exposure, occupancy patterns, heating controls, insulation, and other factors; gas heating is promoted as one of the most economical options for home heating (Sedbuk, 2010).

Table 4 Typical annual fuel costs for gas boilers in two property types (Sedbuk, 2010).

Boiler type	**Seasonal efficiency**	**Flat**	**Semi-detached**
Old boiler - heavy weight	55%	£247	£381
Old boiler - light weight	65%	£209	£323
New boiler - non condensing	75%	£181	£280
New boiler - condensing	88%	£155	£239

2.1.4.5 District heating

2.1.4.5.1 Description of district heating

While district heating (DH) has been deployed in the UK since the 1950's, it has achieved only a low market penetration and currently provides less than 2% of UK heat demand (Poyry et al., 2009) having suffered from a poor image based on the experience of outdated technologies and systems that are 20 to 40 years old and have not been adequately maintained (Roberts, 2008). Notable existing and expanding district heating schemes serving commercial premises, and public and private housing are located in key cities including: Nottingham, Manchester, Southampton and Sheffield, (Enviroenergy, 2013; GMEC, 2013; SCC, 2013; Veolia, 2013). District heating is however already widespread in North, Central and Eastern Europe, where market shares often reach 50% and more (UKGBC, 2010). In Denmark for example, district heating networks have developed on a number of scales, covering whole cities or rural settlements of only 250 inhabitants while other European countries have achieved up to 70% connection rates (LEP, 2007).

Current district heating is often associated with Combined Heat and Power (IEA, 2004) systems with the simultaneous production of electricity and heat, or direct DH systems for housing estates and other sector heat demands (Toke and Fragaki, 2008). Combined CHP-DH is favoured because of the improved efficiency of energy production and use for example; a 1MW simple cycle gas turbine with an electrical efficiency of 22% and a thermal efficiency of 43%, provides an overall efficiency of 65% (Roberts, 2008).

The physical elements of a district heating scheme consist of an energy centre with a central heat source (i.e. gas, biomass or geothermal), a heat distribution network, and space heating and domestic hot water systems within each building and dwelling (Roberts, 2008). Heat transmission and distribution networks generally consist of a pair of highly insulated steel or plastic pipes, one carrying flow water at 90^{o}C to 120^{o}C and one return water after heat has been extracted at temperatures of 40^{o}C to 70^{o}C (Poyry et al., 2009). Heat is transferred to conventional heating systems either directly or indirectly through a heat exchanger or heat station which can provide a separation of the two water based systems, a meter for charging purposes and a pump for water circulation (Poyry et al., 2009; Viessmann, 2010). Other adaptations of district heating included centralised heating for apartment blocks (MHS, 2010) where the heat distribution system in the block is constructed from pipes linking flats to the centralised boilers.

In residential developments, the number of dwellings and the density of the development are important since demands tend to be peaky and, for new build, increasingly strict building regulations are progressively diminishing heating demands, therefore leaving high rise buildings and flats as ideal candidates for district heating (Halcrow, 2008; Roberts, 2008). Heat networks from DH are technology neutral and able to transport heat irrespective of the method of generation i.e. gas, biomass, or geothermal (UKGBC, 2010). Therefore they can form a future-proofed heat distribution framework that can service evolving low carbon generation technologies providing good potential for long-term sustainability (Engineerlive, 2010). However, when district heating systems are installed in city dwellings cooking is normally carried out through the use of electricity (ICARO, 2009).

District heating is most economical on a large-scale where heat density exists which provides efficiency savings to offset the larger capital cost of the required infrastructure (IEA, 2005). With relatively lengthy payback periods developers require a high degree of certainty of customer base to ensure long term system success. Due to the system extent and the land space required for pipes etc. planning difficulties and contractual issues can often occur slowing development and requiring a higher degree of regulation to sanction the necessary infrastructure works and provide a basis for heat up-take (DECC, 2012c; IEA, 2005). Further, the relationship between customer and heat supplier can be different to the normal gas/electricity one as customers may have little choice and suppliers will need to ensure fairness and transparency (IEA, 2005).

Scandinavia particularly Denmark has a wealth of experience in developing district heating systems to provide heat to cities, towns, peri-urban areas and even rural communities. Lessons learnt through implementation include - the need for political action to advocate the introduction of district heating through specific planning rules. This approach has also been enhanced through interaction with and initiatives from municipal and grass-root groups (Toke and Fragaki, 2008). Technically, district heating feasibility and the uptake of alternatives including electric heating are influenced by the distance to existing district heating systems. Thermal stores offer greater flexibility in district heating operation particularly where CHP is employed. The aggregation of the output from several smaller CHP units and associated district heating systems can provide a means to the marketing, tradability and dispatchability of power following a small power station approach (Toke and Fragaki, 2008).

Where significant demand reduction or changes takes place by customers through improved building energy efficiency the balance in favour of district heating systems can change making alternatives such as electric heating more feasible and reducing profitability for system operators (Lund et al., 2010).

2.1.4.5.2 Environmental sustainability of district heating

The high energy efficiency in district heating projects when combined with the use of renewable fuels, makes this technology attractive as a means to reducing emissions of GHG (Bowitz and Dang Trong, 2001). EU wide studies by UKGBC (2010) show that an additional 400 million tonnes of CO_2 could be saved every year if further district heating infrastructure were to be implemented across European countries. DH can play a key role in achieving a balance for CO_2 reduction, security of supply and affordability as heat networks represent a long term strategic investment for moving low carbon/renewable heat around communities (UKGBC, 2010). Studies acknowledge the carbon savings district heating can deliver compared to conventional heating systems (EST, 2008; ICEPT and CES, 2010; Poyry et al., 2009) - see Figure 9. Where district heating can achieve a high penetration (in the region of 80%) in a built up area, the carbon abatement costs of district heating options can be better than most cost effective stand-alone renewable technologies such as heat pumps and biomass boilers (Poyry et al., 2009).

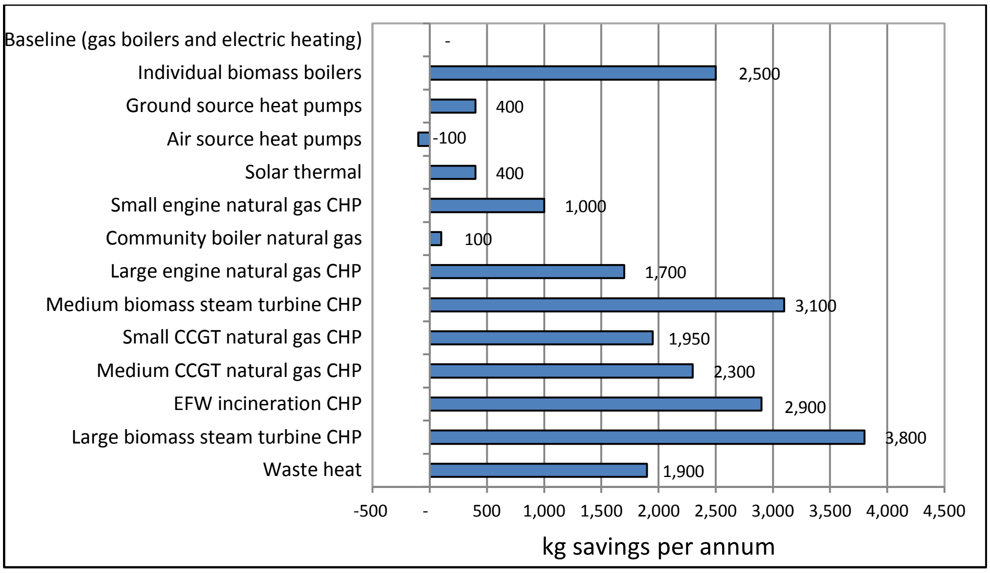


Figure 9 Carbon savings of district heating options compared to baseline gas boilers (Poyry et al., 2009).

From a manufacturing and installation perspective; Oliver-Sola et al (2009) shows that the sources of environmental impact for district heating systems are not particularly located in the main pipe network (less than 7.1% contribution in all impact categories), but in the power plants and dwelling components with heat exchangers and the service pipes exhibiting a high impact contribution.

2.1.4.5.3 Economic sustainability of district heating

Low penetration rates for district heating to date can be attributed to the relatively high cost of installed systems compared with conventional gas or electric based heating systems; particularly the cost of hot water pipes (Poyry et al., 2009). Furthermore the average cost of heat through district heating systems is still more expensive than the baseline technologies including individual gas boilers (Poyry et al., 2009) – see Figure 10. However, there are a number of combinations of fuel and building types that can reduce the relative costs: using waste heat from conveniently sited power stations, replacing electric heating systems with DH and supplying high rise flats in high density areas. In order for there to be the necessary investment in community infrastructure, any financial model must deliver the required financial returns to investors (UKGBC, 2010) and without a shift in the market or regulatory environment, there will be no significant additional take up of district heating for existing building stock and particularly in the domestic sector (Poyry et al., 2009).

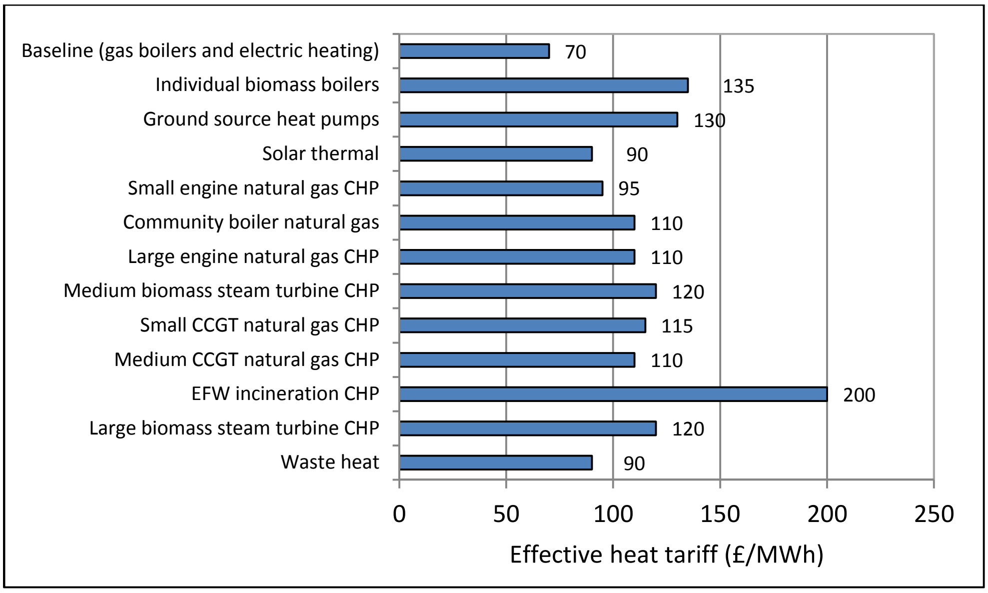


Figure 10 Cost of heat provision by technology type (£MWh) (Poyry et al., 2009).

2.1.4.6 Combined heat and power (CHP)

Following on from the review of the district heating system – a similar system also used with hot water distribution networks to households is the CHP. The CHP generates both heat and electricity.

2.1.4.6.1 Description of CHP technologies

Current district heating is often associated with combined heat and power (CHP) systems with the simultaneous production of electricity and heat, or direct district heating systems for housing estates and other sector heat demands (Toke and Fragaki, 2008). CHP is defined as the recovery and use of waste heat from power generation (CarbonTrust, 2010); designs can boost overall conversion efficiencies to over 80% (IPCC, 2007). Its use in district heating schemes or within community heating systems such as apartment blocks is increasingly being promoted as part of the drive toward low carbon energy solutions (IEA, 2011). However, Toke and Fragaki (2008) observed that in the UK, electricity production from CHP amounted to around only 9% of UK electricity consumption in 2005 and that only 350 MWe was in the buildings sector representing just 6% of the UK total CHP capacity valued at around 5,600 MWe.

Generally CHP technologies and associated systems can range from 5 kWe to over 500 MWe (IPCC, 2007), with small packaged CHP systems typically sized between 60 kWe and 1.5 MWe (CarbonTrust, 2010). Elsewhere small scale CHP is defined as those having electrical outputs of up to about 1 MWe (ETSU, 1996) and are usually based on gas reciprocating engines. These often come as complete packaged units ready for connection into the building or heat systems network – a typical CHP system is shown in Figure 11.

CHP technologies generally consist of four basic elements: a prime mover, an electricity generator, a heat recovery system and a control system (IEA, 2011; CarbonTrust, 2010). A range of prime movers are used in CHP systems including - internal combustion engines, steam turbines, gas turbines, Stirling engines and fuel cells. Heat recovery equipment captures the heat from the prime mover and provides a route for it to be used, for example, water heating in community heating systems.

Common fuels used include; natural gas, other gases such as biogas, and biomass, heavy oils and waste materials. Further parallel technologies maybe required to provide power and heat during start up, supply shortfalls, maintenance or more commonly to meet peak demands.

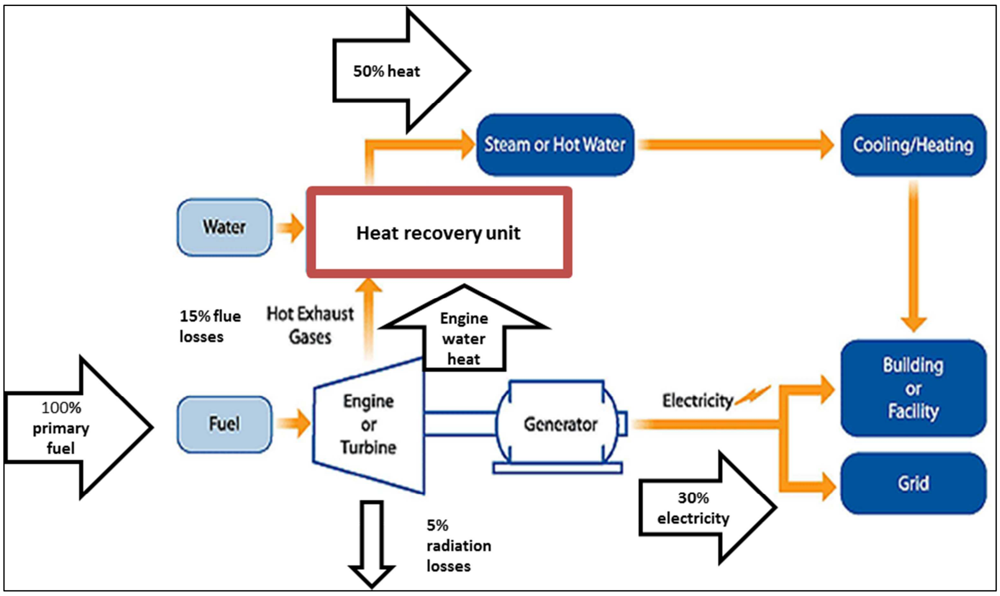


Figure 11 Typical CHP system for use in a small scale district heating scheme.
[Adapted from (EPA, 2013; ETSU, 1996)].

2.1.4.6.2 Environmental sustainability of CHP technologies

CHP systems can deliver an overall efficiency of around 85% (Bellingham, 2010), and with efficient district heating systems providing heat to households, network losses could range from 6 to 9% (Bellingham, 2010). Carbon savings from the use of small and large engine natural gas CHP units are 1,000 kg and 1,700 kg per annum respectively when compared to individual gas boilers (Poyry et al., 2009). Elsewhere, IPCC (2007) suggest that there is an overall environmental benefit through a reduction of 160–500 g CO_2 per kWh when using fossil fuels for combined heat and power. Carbon savings for gas CHP are however directly related to the grid carbon intensity and would need to decarbonise down to below 0.24 kg per kWh for gas savings to be eliminated (EST, 2008). Possible cost of CO_2 savings from gas CHP are shown in Table 5.

For any scheme, CHP technologies and systems need to consider the ratio of heat and electric power to ensure maximum efficiency of the unit and that demands are met effectively. Current internal combustion type CHP units tend to provide more heat than electricity despite exhibiting high overall efficiencies (IEA, 2011). Thermal stores installed can help to use the heat and electricity more efficiently through storage at low heat demand periods while generating electricity for localised use or export to the grid (Micanovic and Brinckerhoff, 2012).

Table 5 Cost of CO_2 saving from gas CHP compared to individual gas boilers(EST, 2008).

	Medium communities (50 flats) £ per tonne CO_2	**Large communities (500 flats) £ per tonne CO_2**
Town centre flats (G3, G4)	-50	-250
Urban dense flats (H3, H4)	+100	-200
New build urban dense flats (I3, I4)	+150	-180

[Negative cost show savings. Letter number suffix relate to the study housing type categories].

2.1.4.6.3 Economic sustainability of CHP technologies

DEFRA (2007a) outlined the economic potential for CHP in the UK at the industrial, community and individual household levels. For industrial applications CHP is particularly economical, however the potential for CHP lies in a small number of large opportunities (DEFRA, 2007a). Within individual buildings; there is a significant additional potential for cost effective CHP installations (DEFRA, 2007a), however the majority of potential is to be found in public and commercial buildings. CarbonTrust (2010) suggest that to make CHP economical there needs to be at least 4,500 hours per year of high and constant heat demand.

Typical costs of heat provision by technologies were previously shown in Figure 12. Small and large engine CHP using natural gas within a small to medium scale district heating network effectively has a heat tariff of £95 per MWh and £110 per MWh respectively compared to £75 per MWh for individual natural gas boilers (Poyry et al., 2009). Elsewhere EST (2008) has calculated the costs for the delivery of heat from gas fuelled CHP units to different urban communities – examples are shown in Table 6.

The CHP quality assurance programme (CHPQA) encourages the development of CHP through various benefits including: climate change levy exemption, enhanced capital allowances, and exemption from business rating of CHP plant and machinery (DECC, 2000). DECC (2009a) defines 'good quality' through a practical method of assessment considering efficiency through inputs, outputs, fuel and capacity; and includes the criterion that power supplied is more valuable than heat supplied. The renewable heat incentive (RHI) is paid for CHP operation depending on the thermal output and fuel type used for the CHP unit – however current incentives are not available where natural gas is used (DECC, 2013c) although CHP using biomass including municipal solid waste and bio-methane are covered. Elsewhere, issues surround the poor rates of return in selling electricity produced by CHP schemes to the national grid. Improved rates are often obtained by using private wire systems to sell premium rate electricity to households in the CHP and district heating schemes (DEFRA, 2007a); there are further constraints in obtaining connections to the local grid.

Table 6 Cost of heat energy delivered from gas CHP (EST, 2008).

	Medium communities (50 flats) £ per MWh	**Large communities (500 flats) £ per MWh**
Town centre flats (G3, G4)	75*	40
Urban dense flats (H3, H4)	130*	50*
New build urban dense flats (I3, I4)	175	95*

[* Gas CHP provides energy at a cost comparable or cheaper than conventional gas boilers].

2.1.4.7 Solar thermal

2.1.4.7.1 Description of solar thermal

The average sunshine falling on a horizontal surface in the UK is between 94 W/m^2 in Edinburgh and 109 W/m^2 in London (Mackay, 2008) with each square metre of a south facing roof in Britain receiving around 1,000 kWh of solar radiation during a year (SES, 2010). Although these are relatively low compared to other parts of Europe, it is considered that in Britain solar thermal has the potential to provide most of an average families hot water requirements from about May to September and to obtain some 'pre-heating' of the cold water supply during the other months (SES, 2010).

Solar thermal refers to the absorption of solar energy as heat into water using a purpose-built collector (NERA and AEA, 2009). Solar thermal is a proven and established technology that uses solar energy heat from the sun to heat domestic water for households use (GED, 2010). A typical system comprises of a solar water heating panel (collector), water tank (including heat exchanger), external support and piping for thermal fluid and sanitary water flows (Belessiotis et al., 2009). The main type of collector used for solar thermal systems are evacuated tubes and flat plates (Carbontrust, 2008). They differ in that the former absorb heat using heat absorbent materials and the later absorb heat using the fluid circulating within them. In the UK the fluid is then typically pumped through the system to heat the water and stored in a hot water cylinder, although thermo-siphon, or passive systems (which are the more widely used elsewhere), use natural convection to transport the fluid from the collector to the hot water tank above.

The quantity of hot water generated by solar thermal systems is measured as a solar fraction (% of hot water demand met by solar thermal water heating) (CIBSE, 2010c). Several factors influence the solar fraction, including a household’s hot water demand, climate conditions, and systems design and performance characteristics. In terms of climate, a collector must receive sufficient solar energy for the majority of the day to produce adequate hot water. Since solar energy is relatively reliable and predictable it is possible to identify locations that receive sufficient solar energy. The locations should also be free from shade, be southerly facing and the house must also possess a strong roof with sufficient space (Miller, 2005). In a typical domestic system, the solar heating source is often supplemented by either an electric emission type heater or a gas boiler (HoC, 2010) and consist of 4 m^2 of evacuated solar thermal tubes combined with 250 litre twin coil insulated thermal store, expansion tank, diverter valve, pump station and controller (HoC, 2010).

More sophisticated applications of solar heat are possible in larger buildings and industrial environments. Standard solar hot water collectors provide water temperatures of 60 to 100°C, which is sufficient for applications such as food processing and desalination (IEA, 2010a). The installation of large solar thermal on apartment blocks in the UK is a recent phenomenon, however current examples include: Killick House, Sutton (SolarUK, 2005) serving 53 flats, and The Green Building, Manchester with 60 m^2 of solar collector, (Viessmann, 2008). However, literature reviews show no studies have been performed to date on apartment block scale solar thermal systems using a life cycle approach.

2.1.4.7.2 Environmental sustainability of solar thermal

Solar thermal heating systems have the potential to provide an average UK household with up to 70% of domestic hot water needs as well as space heating, and can therefore make a sizable difference to domestic energy demand (Appleyard, 2009; BRE, 2009b). In highly insulated homes, the reduction in demand for space heating magnifies the importance of the water heating requirements, which are relatively constant and depends on occupant behaviour. In addition, domestic hot water needs a temperature of 50^{o}C to 60^{o}C compared with a 20^{o}C to 22^{o}C for space heating, which is more energy intense (IEA, 2010b). Recent studies BRE (2009b) over a 12 month period showed that the solar panels had provided 57% of the heat energy input to the hot water cylinder, saving a possible 1,850 kWh per year in fuel compared to a high efficiency gas condensing boiler.

The environmental sustainability of solar thermal systems is typically determined in the published literature by comparing their GHG emissions, primary energy consumption and energy and emission payback times, with conventional heating systems (Kalogirou, 2004). Although other environmental impacts have been examined, they are generally poorly represented in literature. These studies demonstrate the ability of solar thermal systems to save GHG emissions and reduce primary energy consumption and therefore reduce fossils fuel depletion (Kalogirou, 2004). The greatest environmental benefits are observed when solar thermal systems replace the worst environmentally performing energy supply options such as electric and oil heating systems and this aspect is also generally recognised and promoted by government (DECC, 2010d).

The manufacturing stage is generally the largest contributor to the environmental impacts (Bergerson and Lave, 2002). Within conventional systems the greatest impacts are from the operation of the technology through the supply of fuel and maintenance. The disposal life cycle stage tends to have a very small contribution to the environmental impact categories investigated (around 2%), except for solid waste related indicators (Battisti and Corrado, 2005). The environmental impacts associated with the manufacturing stage arise mainly from the manufacturing of the solar panel (Ardente et al., 2005). Copper and aluminium used for the metal framing of the panel are the largest contributors to panel and water tank manufacturing since production and processing of these materials is highly energy intensive and there are environmental impacts such as heavy metal, carcinogens and the consumption of energy sources associated with the mining and waste of these materials (Ardente et al., 2005; Battisti and Corrado, 2005). Some of the environmental impacts associated with solar thermal systems can be alleviated however by - replacing copper tubing with steel tubing and through the use of recycled aluminium. Further studies are needed to determine the environmental impact of vacuum tube manufacturing and disposal.

2.1.4.7.3 Economic sustainability of solar thermal

The main cost for solar hot water systems is the installation itself, although they can be incorporated into new buildings with minimal overhead cost (Ekins-Daukes, 2009). The solar thermal option is not currently economically competitive with conventional technologies however, with increased production volumes and technical improvements, the capital costs could be reduced and improve sustainability (Allen et al., 2009).

Typical panel costs for a domestic home in the UK are around £1,440 however actual installation costs push this figure up to £4,000 (Ekins-Daukes, 2009). For new buildings, the installation costs can be subsumed into the overall construction costs with minimal impact to the overall budget (Ekins-Daukes, 2009). NERA and AEA (2009) suggest that there is significant potential for renewable heat to supply much of the market currently served by fossil fuels or electric heating, however the per unit cost of solar thermal is higher than determined previously, significantly exceeding that of other renewable heat technologies such as heat pumps.

It is therefore not clear whether solar thermal could play a realistic overall role on its own or a supportive role to other technologies in city dwelling energy supply and emission reduction hence a focus of this research.

2.2 Social sustainability

2.2.1 Introduction

Social sustainability is considered as one of the pillars of sustainability along with environmental and economic. At the forefront of development social sustainability thinking and definition was the Bruntland report, *Our common Future*, (WCED, 1987). The report laid out the concept of sustainability as containing environmental, economic and social aspects. However, the social dimensions have often been sub-servant to the other two aspects (Markku, 2004), whilst, the concept of sustainability is frequently re-designed by organisations according to their particular purposes and context.

Further studies consider the social dimension as bipolar - recognising both individual and collective levels (Markku, 2004). Vallance (2011) seeks to express social sustainability within the dimensions of: development (ranging from potable water to equity and justice), bridge (better connections between people and bio-physical environment) and maintenance (continuation of practices, preferences and places). Furthermore, Benoît and Vickery-Niederman (2010) consider social sustainability in the context of social responsibility and the way that organisations conduct business. They have identified six main types of references and instruments relevant to social sustainability assessment: International Policy Frameworks, Codes of Conduct and Principles, Sustainability Reporting Frameworks, Social Responsibility Implementation Guidelines, Auditing and Monitoring Frameworks and Financial Indices.

Methodologies for social sustainability assessments include: Social Impact Assessment, Human Rights Impact Assessment and Value Chain Analysis. However, Assefa and Frostell (2007) seek to define social sustainability in terms of the developed system consisting of: fairness in distribution and opportunity, adequate provision of social services including health and education, gender equality and political accountability and participation. Assefa and Frostell (2007) then go on to suggest that, measuring and quantifying the social dimension of sustainability are difficult tasks especially agreeing the objective definition of social sustainability. Sachs (1999) suggests social sustainability as - the social preconditions for sustainable development or the need to sustain specific structures and customs in communities and societies. Others look at individuals, communities and societies (Colantonio, 2009) and how they live with each other, set out to achieve objectives that they themselves have chosen within their physical boundaries along with that of the planet. Colantonio (2009) further considers that traditional social sustainability themes include – human rights and employment but recognises that emerging themes also include: happiness, well-being, quality of life and health and safety.

2.2.2 Sustainability indicators, sustainable communities and energy

Several studies have sort to use indicators as a means to measuring social sustainability especially those related to the energy sector (Carrera and Mack, 2010; Evans et al., 2009). Typical indicators include: perceived health risks, safety management, and equity (Roth et al., 2009); aesthetic impacts, participation, and innovative ability (Carrera and Mack, 2010); and personal control and potential of terrorist attack (NEEDS, 2006). However, Colantonio and Dixon (2006) recognise that there is a shift, from one of statistics based indicators towards a hybrid set of indicators that mix quantitative data and qualitative information.

Communities that exhibit the qualities of environmental, economic and social sustainability are considered as sustainable communities. Exemplar sustainable community projects with social and cultural perspectives consider sustainable communities as being - vibrant, harmonious and inclusive (Cities, 2005; ODPM, 2004a; ODPM, 2004b). The previous government enshrined in the *Sustainable Communities Act*, powers by which communities can for example; influence government action and assist in the challenges of sustainability and well-being (CaLG, 2007e).

Nevertheless, when considering sustainability and energy interventions, the manufacture, installation, and operation of new and replacement energy technologies and systems will invariably have both positive and negative impacts on people and communities. Vanclay (2003) describes a number of those impacts within social impact assessments as “changes to peoples”:

- community - stability, cohesion, services, and facilities;
- political systems - participation in decisions;
- way of life - how they live, work, play;
- environment - availability, quality, and access;
- fears and aspirations - perception of safety, and future;
- health and well-being[4] - as defined by World Health Organisation (WHO, 2000);
- personal and property rights - human rights; and
- culture - shared beliefs, customs, values.

According to Assefa and Frostell (2007), when studying future energy systems, accounting for the role of the social aspects brings up the benefit of avoiding sub-optimisation. Therefore, to achieve an optimum solution in terms of social sustainability outcomes, it is important to understand what stakeholders think and feel concerning current and future energy issues – hence the intension of this research.

2.2.3 Social sustainability research design

Traditional research designs usually rely on a literature review leading to the formation of a hypothesis and the hypothesis is then put to the test by experimentation in the real world (Allen, 2003). Field research though must seek out contradictions and contrary evidence – the building up of theory must be associated with the search for knocking it down again. The validity and appropriateness of qualitative data analysis according to research perspectives have been outlined by Flick (2002) showing: theoretical positions, methods of generation and methods of interpretation - see Table 7.

Symbolic interaction, as the theoretical position, serves well in situations where the focus is on what people think about particular issues. Symbolic interactionism is described by Klunklin and Greenwood (2006) as - theoretically focused on the acting individual; where the individual is regarded as determining rather than determined, and

[4] Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity WHO 2000. Air Quality Guidelines for Europe World Health Organization Regional Office for Europe Copenhagen WHO Regional Publications, European Series, No. 91 Second Edition. *WHO Regional Publications, European Series, No. 91*.

society is constructed through the purposive interactions of individuals and groups. The central concepts of symbolic interactionism therefore includes: the self, the world, and social action (Charon, 1995) and where:

- The self is constructed through 'social interaction' with others and then others in ever widening social circles – helping to form beliefs and attitudes;
- The world refers to a world of 'symbols', where not all objects are symbols but objects (houses, family, culture) become symbols when meaning is assigned to them (Klunklin and Greenwood, 2006); and
- Social action purports to the process where individuals 'fit their actions together – this is often conducted in complex, dynamic social contexts; and therefore to appreciate this fully, it often requires its observation and interpretation in the relevant contexts.

Table 7 Selecting appropriate methods for qualitative data analysis (Flick, 2002).

Research perspective	**Subjects points of view**	**Making of social realities**	**Cultural framing of social realities**
Theoretical positions:	Symbolic interactionism.	Ethnomethodology Social constructionism.	Psychoanalysis Genetic structuralism.
Methods of data generation:	Semi-structured interviews Narrative interviews.	Focus groups Ethnography Participant observation Recording interactions Documents.	Recording interactions Photography Film.
Methods of interpretation:	Thematic coding Content analysis Narrative analysis Hermeneutic methods.	Conversation analysis Discourse analysis.	Objective hermeneutics Deep hermeneutics.

It is generally acknowledged that symbolic interactionism and grounded theory are connected (Klunklin and Greenwood, 2006), *grounded theory* is the method of symbolic interactionism, and the methodological principles and similarities are shown in Table 8.

Used correctly, symbolic interactionism allows analysts to explain rather than merely describe the behaviours, strategies and perceptions behind, for example - energy systems and social sustainability.

Table 8 Symbolic interactionism methodological principles compared to those of grounded theory (Klunklin and Greenwood, 2006).

Symbolic interactionism	Grounded theory
• Direct observation of empirical world • Determination of data through disciplined observation • Raising of abstract problems • Construction of categories • Construction of theoretical scheme • Testing of categories.	• Participant observation, interviewing, document analysis, videotaping, etc. • Observation, interviewing guidelines, theoretical sampling • Analytic, methodologic, personal memoing • Open coding, axial coding, theoretical coding, properties, dimensions • Core category, categories, subcategories, properties, dimensions, memos, and diagrams • Theoretical sampling, theoretical saturation, literature review, group analysis, member checks.

Grounded Theory is used as the basis for qualitative research. A *grounded theory* approach can be conducted to explore substantive areas so as to gain novel understanding. *Grounded theory* investigates the actualities in the real world and conducts analyses of the data with no preconceived hypothesis (Glaser and Strauss, 1967). Because emergence of theory is the foundation of this approach to theory building; researchers do not enter an investigation with a list of preconceived concepts, a guiding theoretical framework, or detailed design. However, concepts and designs are allowed to emerge from the data.

Strauss and Corbin (1998) have encouraged researchers to “use any material bearing in the area”, thus literature searches are considered as a basis of professional and accumulated knowledge. Analysis of interview data in typical qualitative research tends to result in descriptions of an interpretist view of events, whereas *grounded theory* data analysis involves searching out the concepts behind the actualities by looking for *codes*, then *concepts* and finally *categories* (Allen, 2003). By using a *grounded theory* approach, the resultant theory does not need separate justification and testing because it comes from live data (Allen, 2003). It is recognised that within any research there will be interplay between qualitative and quantitative theorising. The issue is not primacy but rather when and how each mode might be useful to theorising (McKeganey, 1995).

2.3 Air quality monitoring – direct emissions

There is increasing concern being expressed about the effects of indoor air quality on health (Jones et al., 2002). Improvements in residential house insulation have reduced air infiltration while allowing ventilation to be more or less standardised (HMGOV, 2010). Such changes allow the build-up in concentrations of gases and emissions derived from heating, cooking and other sources and inevitably this could impact on people living within homes. This aspect is mainly through the emissions connected with fuel combustion and the cooking of food. It has been acknowledged that the inhalation of indoor air is the major determinant of human exposure to many pollutants (Brown et al., 1994). Indoor air emissions from the use of energy and associated studies are now described.

2.3.1 Carbon Monoxide (CO)

Carbon monoxide is a colourless, odourless, tasteless gas formed from the incomplete combustion of fossil fuels (Mandal et al., 2010). CO is also a poisonous gas and can cause mortality or morbidity through inadequate indoor ventilation or faults in gas heating or cooking appliances. An early symptom of carbon monoxide poisoning is headache, often presenting itself at carboxyhemogtobin levels greater than 10% (Paul S, 1987), other symptoms include - dizziness, weakness, nausea, confusion, disorientation, and visual disturbances (Raub et al., 2000). Studies have found it difficult to determine the actual burden of disease due to CO (Mandal et al., 2010), while it is estimated that approximately 50 deaths occur each year in the UK from CO (Mandal et al., 2010).

Air quality studies conducted in London have demonstrated that a large proportion of homes (18%) exceeded one or more of the WHO guideline values for carbon monoxide (Croxford et al., 2006). The main causes were identified as old and poorly maintained gas appliances, generally either the cooker or a gas fire. In the study the occupants of homes with faulty appliances were often elderly and vulnerable people.

Croxford et al (2006) suggests that, CO concentrations found in different homes have their own pattern and depend on many factors that may include:

- where the CO comes from (source);
- how effectively it is removed by ventilation;

- the condition of any gas fired appliances in the home;
- the way these appliances are used; and
- the type of ventilation present in the home.

Raub et al. (2000) indicates that, outdoor concentrations of CO are highest near street junctions, in congested traffic, and near exhaust gases from internal combustion engines. Furthermore, CO concentrations indoors are highest in homes that have faulty or poorly vented combustion appliances, but also homes where smoking takes place (Raub et al., 2000).

2.3.2 Volatile organic compounds (VOCs).

The volatile organic compounds are a group of chemicals that are both diverse and numerous, have many sources and are potential harmful to human health (Parra et al., 2008). These are particularly important substances which can arise from sources including paints, varnishes, solvents, and preservatives (Jones et al., 2002). There are differences and changes in VOC and TVOC levels between new and existing housing with construction products contributing to VOCs in new housing and household products on more established housing (Jarnstrom et al., 2006; Brown et al., 1994).

Several studies have considered VOCs, Jarnstrom et al (2006) studied indoor air in new buildings and Winkle and Scheff (2001) as part of a public health assessment. Elsewhere, in non-smoking bars and restaurants, sources of VOCs included: outside traffic, air fresheners, cleaning products, and paints (Parra et al., 2008). In homes, elevated indoor VOC concentrations were associated with the presence of an attached garage, recent renovations, older residences and indoor smoking (Jia et al., 2008). Further studies demonstrate the complex nature of VOCs and sources - increased levels due to fresh newspapers and dampness are indicated (Schlink et al., 2010). This is possibly due to dampness intensifying the emission of VOCs from furniture and building materials, tests also demonstrated that freshly printed newspapers, located next to samplers, dramatically increased the recorded amount of toluene.

2.3.3 Nitrogen Dioxide (NO_2).

Nitrogen dioxide is an nasty smelling irritant gas that can have both acute and chronic respiratory effects and can contribute to the formation of photochemical smog (Latza et al., 2009; DoSEWPC, 2011). Concentrations of nitrogen dioxide, can be significant in the indoor and outdoor environment and is considered as being hazardous to health (Kornartit et al., 2010). Outdoor sources derive from mobile and stationary combustion sources (Kornartit et al., 2010), while those indoors include gas cookers and gas fires.

Kornartit et al (2010) found that NO_2 indoor concentrations were higher in the winter when using gas for cooking but with little difference compared to the outside during the summer. Concentrations in the kitchen were found to be twice as high when using a gas cooking compared to using electricity (Kornartit et al., 2010). Elsewhere, NO_2 levels in New York apartments using gas stoves showed readings from 47 μg per m^3 to 237 μg per m^3 (Bodian et al., 1989). NO_2 levels were influenced by factors within an apartment with high correlations between NO_2 levels in different rooms of the same apartment. Within the WHO guidelines (WHO, 2010), it was assumed that having a gas stove was equivalent to an increased average indoor level of 28 μg per m^3 compared to an electric stove. Where there were no indoor sources of $NO_{2,}$ concentrations were estimated at 15 μg per m^3.

2.3.4 Sulphur Dioxide (SO_2)

Sulphur dioxide is a colourless gas with a sharp odour and is produced from the burning of fossil fuels, usually coal and oil. The main anthropogenic source of SO_2 is the burning of sulphur containing fossil fuels for domestic heating, power generation and motor vehicles (WHO, 2011). Katsouyanni et al (1997) report that, in western European cities it was found that an increase of 50 μg per m^3 in sulphur dioxide or black smoke was associated with a 3% increase in daily mortality and the effects stronger during the summer. They go on to suggest that, the long term health impact of the effects is uncertain, but today's relatively low levels of sulphur dioxide still have detectable short term effects on health. Further studies in Europe (Namiesnik et al., 1992; Stranger et al., 2009) have found, indoor SO_2 levels to be lower than those outdoors; possibly due to better mixing of air and absorption of SO_2 by building materials and furnishings.

2.3.5 Carbon dioxide (CO_2).

Nearly 18% of global CO_2 emissions are attributed to energy and fuel use by the residential sector (IEA, 2008). Humans are the main indoor source of carbon dioxide but high levels can cause drowsiness and headaches. The indoor levels of CO_2 are an indicator of air ventilation compared to indoor occupant density.

2.3.6 Other studies

Wider studies have been conducted by Fortmann et al (2001) in California and Olson and Burke (2006) in North Carolina to establish levels of CO, NO, NO_2 and Particulate Materials during cooking and heating events. Real time cooking tests were conducted using a range of monitoring methods and cooking appliances including: gas and electric cookers and hobs and microwave ovens (Fortmann et al., 2001; Olson and Burke, 2006). Personal monitors showed readings nine times higher on average than the room monitors. Mean source strengths were two times greater for electric cooking than gas cooking – but with the three highest strengths removed (caused from frying) this reduced to 30% from 80%.

Common sources of household pollutants are shown in Figure 12 and the current acceptable levels for each are shown in 11 Appendix 1.

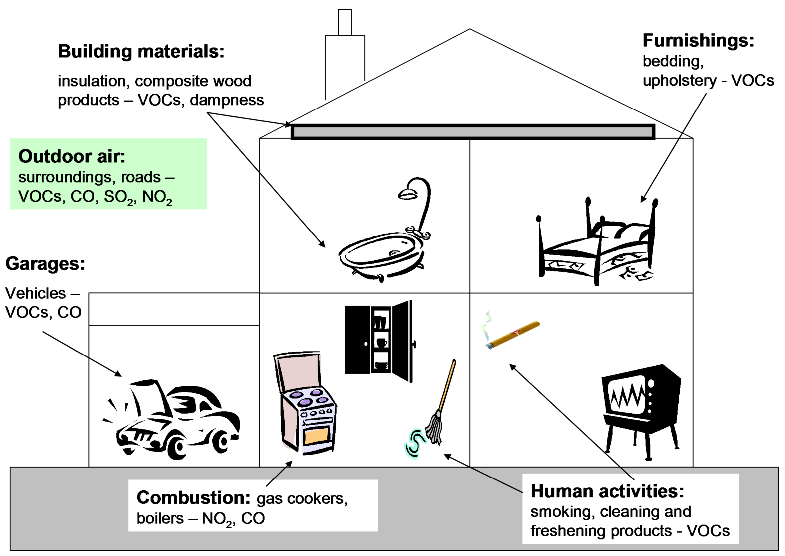


Figure 12: Typical pollutants found within homes.

2.4 Summary of heat electrification, heating technologies and sustainability

The review of the literature has shown that the electrification of heat as a trend exists and is illustrated through the support given to the rapid electrification of both space and water heating in city centre homes from housing developers, utilities and policies to date. The Low Carbon Transition Plan and recent Carbon Plan provide a route to CO_2 emission reductions through the decarbonising of the energy system but an implication of this approach is an increase in the provision of heat from electricity and thereby possibly driving up electrical demand.

This review has shown that research into the environmental, economic and social sustainability of technologies and their associated systems on a life cycle basis is poorly represented in literature. In addition, few studies consider the sustainability of heat-providing systems under different energy scenarios.

This study provides a significant contribution to the understanding of electrification of heat, its implications and the impacts of heat technologies by performing an integrated sustainability assessment – the study methodology and approach is described in the next chapter.

3. Methodology: a framework for sustainability assessment of the electrification of heat

This chapter discusses the methodology developed and used in this study. The methodology here is the result of extended research across the relevant literature, as discussed in the previous chapter, as well as the integration of practical case studies and stakeholder interactions concerning the electrification of heat. The chapter begins with an overview of the methodology, followed by a discussion of its component parts.

3.1 Methodology overview

The methodology follows a life cycle approach and takes into consideration the assessment of environmental, economic and social sustainability. This is outlined in Figure 13. The methodology has five stages as follows:

1) selection of tools for environmental, techno-economic and social sustainability assessment along the life cycle of heat-providing systems;
2) sustainability assessment of selected individual heat-providing technologies;
3) sustainability assessment of different scenarios related to future heat provision;
4) multi-criteria decision analysis (MCDA) of the selected heat-providing systems and scenarios to identify most sustainable options; and
5) Results and recommendations of the sustainability assessment.

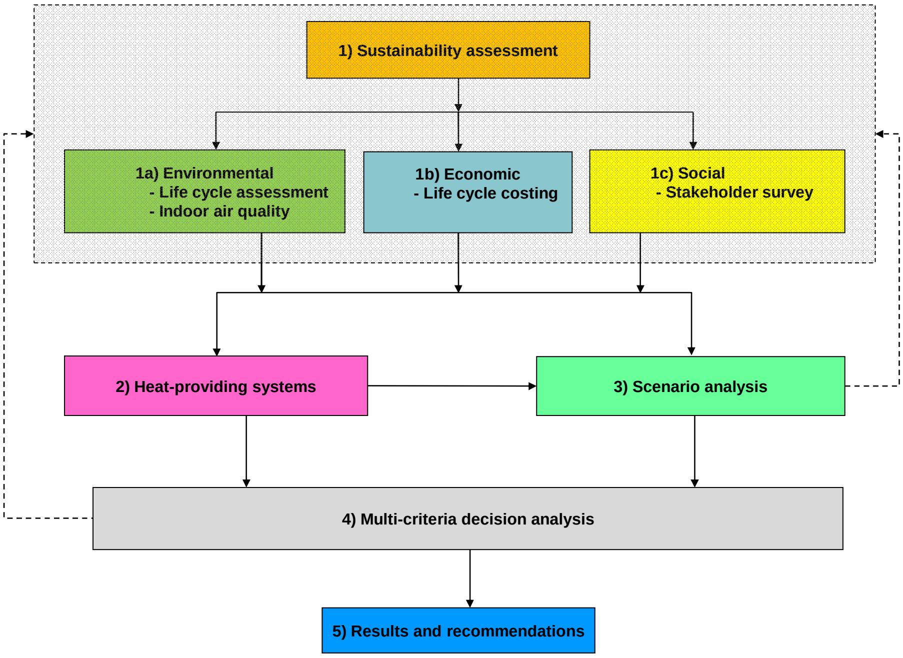


Figure 13 Research methodology – electrification of heat.

3.2 Methodology description

The stages of the methodology are now described in detail - the numbers in brackets refer to those in Figure 13.

3.2.1 Environmental sustainability (1a)

Environmental sustainability was evaluated using two tools: life cycle assessment (LCA) (ISO, 2006b) and air quality monitoring (AQM) (Crump et al., 2002). Life cycle assessment was used to calculate and assess the life cycle impacts of heat producing systems and air quality monitoring of the air emissions associated with typical systems. Both tools and the approaches used in the study are described below.

3.2.1.1 Life cycle assessment

Life cycle assessment is a methodology for evaluating the environmental load of processes and products during their life cycle from cradle to grave (Ortiz et al., 2009). This study considers heat producing systems following the cradle to grave approach. This includes the extraction of raw materials, manufacturing of components, heat system assembly and installation, transportation, conversion of fuels, system operation, maintenance, and replacement of components and final dismantling and disposal of the system.

The life cycle impacts from systems producing space heating, water heating and cooking have been considered. The materials from the equipment, components and life cycle for each heat system were calculated based on those installed within the selected apartment blocks, chosen for study. The assessment was performed using the GaBi LCA software package (version 4.4) (PE, 2010). The most widely used CML 2 Baseline 2001 methodology has been used to calculate the LCA impacts (CML, 2001). The environmental impact indicators used in the study are described below with more detail given in 12 Appendix 2**.**

Environmental impacts

- *Acidification Potential (AP)* - this indicator is a measure of the acidic emissions such as sulphur and nitrogen oxides. It is expressed as sulphur dioxide equivalent (SO_2 eq.).
- *Eutrophication potential (EP)* - increased concentrations of nitrates and phosphates in water can encourage excessive growth of algae subsequently reducing water oxygen levels and damaging eco-systems (BRE, 2005b). This indicator is expressed as phosphate equivalent (PO_4^{-3} eq.).
- *Freshwater aquatic eco-toxicity potential (FAETP)* - this impact measures the effects of toxic substances on the environment. It is expressed as dichlorobenzene equivalent (DCB eq.).
- *Global warming potential (GWP)* - this indicator is a measure of greenhouse gas (GHG) emissions such as carbon dioxide, methane and nitrous oxide and is expressed as carbon dioxide equivalent (CO_2 eq.).
- *Marine aquatic eco-toxicity potential (MAETP)* - similar to FAETP, this indicator measures eco-toxicity to marine life. It is also expressed as dichlorobenzene equivalent (DCB eq.).
- *Ozone layer depletion potential (ODP)* - this indicator measures the impact of ozone depleting gases on the ozone layer and is expressed relative to R11 as (R11 eq.).
- *Photochemical ozone creation potential (POCP) (Smog potential)* - In atmospheres containing nitrogen oxides (NO_x) and volatile organic compounds

(VOCs) ozone can be created in the presence of sunlight. POCP is expressed as ethylene equivalent (C_2H_4 eq.).

- *Terrestrial eco-toxicity potential (TETP)* – refers to the impact of toxic substances such as heavy metals to terrestrial eco-systems. TETP is expressed as dichlorobenzene equivalent (DCB eq.).

Social impacts

- *Abiotic resource depletion (ADP fossil)* - this impact category relates to the extraction of scarce fossil fuels for example natural gas and coal and is expressed in MJ of primary energy extracted. It is calculated as part of LCA but is considered a social impact here as it has intergeneration implications (Stamford and Azapagic, 2011).
- *Abiotic resource depletion (ADP elements)* - this impact category relates to the extraction and depletion of minerals such as copper, steel and aluminium. ADP element is expressed as antimony equivalent (Sb eq.). This impact and HTP below, are also calculated as part of LCA, but is considered a social impact for the same reasons as ADP fossil.
- *Human toxicity potential (HTP)* – measures emissions of substances toxic to human health. Human toxicity potential is expressed as dichlorobenzene equivalent (DCB eq.).

3.2.1.2 Indoor air quality assessment (IAQ)

Maintaining good indoor air quality is important in order to prevent adverse effects on the health, comfort and performance of people; this is especially important in homes where a range of activities and processes can impact on the quality of indoor air (Crump et al., 2002). For this reason, air quality monitoring of selected homes was performed to find out if any of the heat-providing systems affect indoor air quality. The findings of this part the work were aimed at complementing those obtained from the LCA studies to allow for comparison and contrasting of direct and life cycle impacts for different heat providing systems.

Monitoring was carried out in nine homes, including detached, semi-detached, terraced houses as well as apartments based in both London and Manchester. The homes were selected through University and personal contacts. Monitoring covered two seasons – the summer and the winter. It was carried out using sensor units developed at The University of Manchester (Fiadzomor et al., 2011). The process is shown in Figure 14.

The monitoring was conducted following the BRE protocol (Crump et al., 2002) to collect primary emission data from homes utilising gas and electricity for heating and cooking. The sensor units measure SO_2 (sulphur dioxide), NO_2 (nitrogen dioxide), CO (carbon monoxide), CO_2 (carbon dioxide), relative humidity and temperature. Each monitoring unit enables the measuring of gas emissions every 60 seconds over a 14 day period using a micro-pump to draw sample air from the environment across sensors – see Figure 15. The data are stored ready for analysis on completion of each monitoring period. This approach is further assisted through the use of detailed user diaries that indicate key cooking and heating events during the monitoring period. Two sensor units were placed within the house (kitchen and living room) and one outdoors in the vicinity of the home - a typical layout is shown in Figure 16.

Once collected, the data were downloaded from each unit to spreadsheets. Initial data analysis was conducted using the spreadsheets with further in-depth analysis performed utilising standard statistical techniques, indoor/outdoor ratios and principal component analysis (Manfren et al., 2010). Principal component analysis is a procedure that allows the relationship between large sets of data to be observed. Through modelling and observations, patterns in the data can be recognised and variations between samples and outlier points determined. Through the use of PCA, hypothesis can be described or validated.

Data analysis for this study considers four homes where data is both complete and of good quality and where the homes are using either gas or electric for heating and cooking. The analysis includes: indoor and outdoor concentrations, the overall average emissions over the 14-day monitoring period, and differences in emission concentration between summer and winter for the same homes. In addition, cooking events are studied to calculate peak emission levels.

Indicators used from the analysis and to inform the study through the MCDA are briefly described below:

IAQ criteria

- *Carbon monoxide (CO)* – the danger from CO is that it displaces the oxygen in the blood forming carboxyhaemoglobin (COHb) and is exceedingly toxic (Crump et al., 2002). Acute poisoning by CO can cause death and a range of serious health implications. CO in homes can be caused by poor operating or unmaintained fossil fuel appliances such as gas fires, boilers or cookers. The concentration of CO is expressed in mg/m^3.
- *Carbon dioxide (CO_2)* – a natural constituent of air and at normal levels is not a danger to health. CO_2 is used as an indicator of ventilation. Its concentration is expressed in mg/m^3.
- *Nitrogen dioxide (NO_2)* – this can impact particularly on child respiratory systems through elevated indoor levels especially through gas cooking (Crump et al., 2002). The concentration of NO_2 is expressed in $\mu g/m^3$.
- *Sulphur dioxide (SO_2)* – this gas is easily soluble in water and can therefore irritate the moist mucus membranes such as in the eyes, throat, nose and airways. High levels of SO_2 exposure can aggravate respiratory diseases. Its concentration is expressed in $\mu g/m^3$.

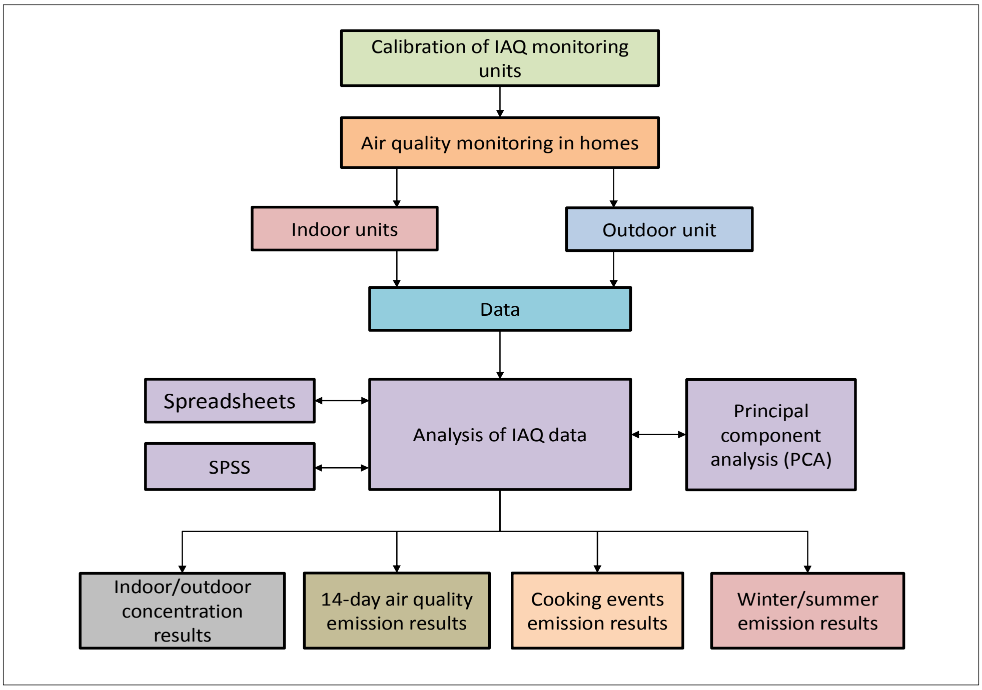


Figure 14 Air quality monitoring methodology.

Figure 15 Air quality sensor unit.

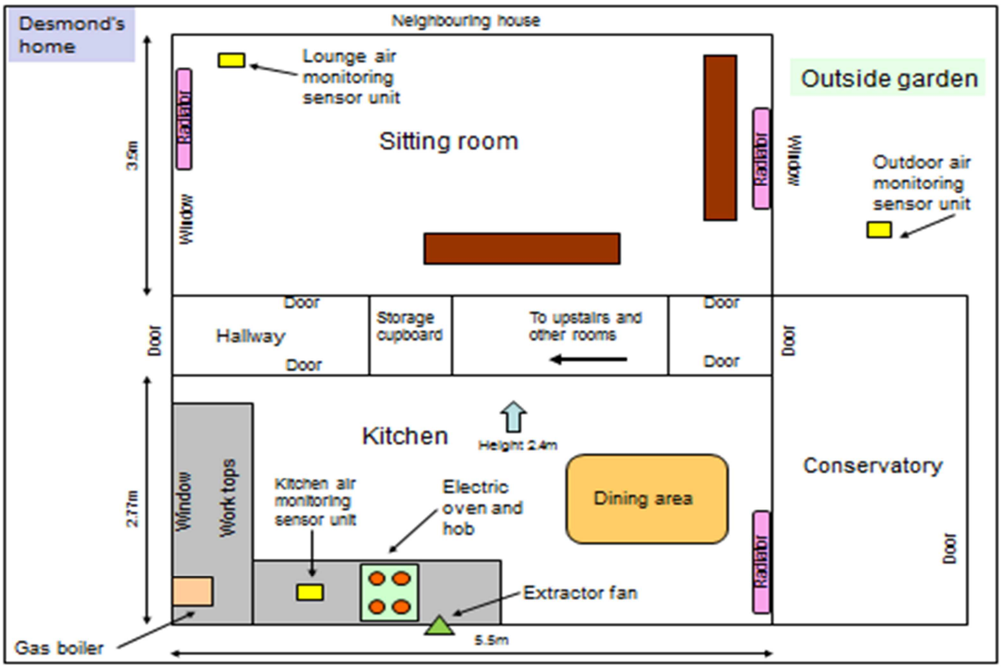


Figure 16 Typical location of air quality monitoring sensor units against house layout.

3.2.2 Economic sustainability (1b)

The economic assessment estimates the economic costs of selected domestic heat-providing options throughout their life cycles using Life cycle costing (LCC). LCC follows the BSRIA guide on whole-life costing analysis (Churcher, 2008).

For this study, the life cycle costs of heat-providing systems are estimated over the 40 year study period. This period was chosen because of the carbon emission reduction targets which refer to the year 2050. The same period is also considered for the future scenarios (see further below).

For this study, case study buildings are considered as the heat providing systems with all energy and construction measures calculated from the point of initial installation and during the 40 year study period. This period was chosen to link closely with current energy scenario timeframes, interim and current emission reduction targets and average lifetimes of installed technologies and systems.

Life cycle costs include capital and operating costs as follows:

- Project planning and management;
- Purchase of equipment and materials;
- Installation and commissioning;
- Planned maintenance and replacement;
- System operation and administration;
- Operational fuel; and
- Decommissioning and final equipment disposal.

Credits to the life cycle costs are also considered and include:

- Scrap valve of any equipment and materials particularly those made from – steel and iron, aluminium, copper, chromium, zinc, and nickel;
- Fuel based incentives such as feed in tariffs and renewable heat incentives; and
- Export of electricity through private cable systems.

The life cycle costs are calculated as follows:

> LCC = $\sum_0^n$ Project planning and management costs + $\sum_0^n$ Equipment and material purchase costs + $\sum_0^n$ System installation and commissioning costs + [$\sum_0^n$ Energy costs x PV_{sum}] + [$\sum_0^n$ Operating and replacement costs x PV_{sum}] + [$\sum_0^n$ Maintenance costs x PV_{sum}] + [$\sum_0^n$ Decommissioning and disposal costs x PV_{sum}] – R x PV.

(where: n = year n, 0 = year 0, PV_{sum} = sum of discount factor, R = residual value (£), r = discount rate, T = system service life, and PV = discount factor.) Note: PV_{sum} = $(1+r)^T$-1/r x $(1+r)^T$ and PV = $1/(1+r)^T$.

Three different discount factors have been used: 0% (present day costs), 5% and 10%.

The costs are defined as follows:

- *Capital costs of system* – refers to the life cycle cost of materials and equipment of the heat providing system including the replacement of items during the 40 year operational period. The indicator is expressed in £ billion.
- *Operation and maintenance cost of system* – addresses the operation of the system including its management and its planned maintenance. The indicator is expressed in £ billion.
- *Fuel costs of system* – refers to the fuel used over the life cycle of the system. Fuels considered include – gas, electricity and heat. The indicator is expressed in £ billion.
- *System costs per kWh* – this indicator measures the overall system cost for each kWh of heat produced by the heating providing system. The unit of measurement is £ /kWh.

3.2.3 Social sustainability (1c)

Social aspects have been explored through:

i) an online questionnaire of users of the heat-providing systems; and

ii) a series of interviews.

The findings have been used to evaluate the social acceptance of heat-providing technologies as well as the current and potential future social impacts of the electrification of heat. The online questionnaire and interviews are described below.

Online questionnaire

Firstly, a small apartment householder pilot survey was conducted to fine tune questions and the survey approach. Secondly, an online questionnaire was developed and made widely available using *Qualtrics* software (Qualtrics, 2011). This system allows questions to be presented to participants systematically online along with supporting information. The questionnaire focussed on householders' existing heating and cooking systems and their perceptions of future all-electric systems and identified factual or objective information known to apartment occupants. The full questionnaire can be found in 13 Appendix 3. Where participants agreed, a limited number of telephone follow-up interviews were conducted to discuss some issues in more depth.

Qualitative data from *Qualtrics* have been analysed using Statistical Package for Social Science (SPSS) (IBM, 2013) and *Qualtrics* itself. From this analysis, techno-economic and social indicators have been identified and developed for each heat-providing system type for further use in the MCDA and scenario analysis.

Stakeholder interviews

Stakeholder interviews were performed to collect primary data as there are few secondary sources of the required data and information that can be directly used for the purpose of this research. In order to ensure a wide representation, stakeholders were selected from organisations and groups considered to have a detailed insight into the issues and impact of energy supply, particularly in cities. Stakeholders identified and consulted include:

- Government and policy makers;
- Councils;
- Developers;
- Utilities;
- Bodies representing energy organisations;
- Manufacturers; and
- Householders,

For a complete list see 13 Appendix 3.

Organisation stakeholders were consulted in individual semi-structured interviews, which consisted of open-ended questions based around the following pre-determined key categories: planning, main drivers and demand, regulations and legislation; space and water heating, emission shifting, energy networks, socio-economics, low-carbon market drivers and impacts and stakeholders. The questions used can be found in 13 Appendix 3. The selection of categories has been made to meet the objectives of this research component and to explore the depth and extent of the stakeholder influences on and around the electrification of heat. A *grounded theory* methodology has been used to analyse the results and for these purposes refinement of the pre-determined categories or the development of further categories was permitted – see previous description in Section 2.2.

Quantitative data obtained have been analysed using SPSS (IBM, 2013) and qualitative data using NVivo (International, 2011) and, as mentioned above, the *grounded theory* method (Allen, 2003; Glaser and Strauss, 1967). From the detailed analysis based on *grounded theory*, categories of importance emerged – these represent links with the original data and connections to the theory – in this case the electrification of heat. First, the emergent *grounded theory* of the electrification of heat has been summarised. Secondly, the categories of importance and their links have been developed into further techno-economic and social impact indicators. Each type of heat-providing system has been assessed against the impact indicators using a rating scale of 1 to 6 for subsequent use in the MCDA and scenario analysis.

3.2.4 Heat-providing systems (2)

Eight heat-providing systems have been considered as installed in apartment blocks in Manchester, Sheffield, Gateshead and London. The blocks are essentially the same in size and construction but have different heat-providing systems. The following systems are installed in the different buildings:

- Electric panel – Emmeline building;
- Electric storage - Thomas Court;
- Communal air source heat pump – FriarsWharf;
- Individual gas boilers - Roach Court;
- Combined gas and electric - Sylvia and Christabel buildings;
- District heating – Coley building;
- Combined heat and power – CHIPs building; and
- Combined solar thermal and gas – Northpoint building.

Technical specifications and system performance details have been obtained through site visits and discussions with building managers and occupants for each apartment block – these have contributed to the LCA, LCC and Social assessment. The pilot apartment survey was conducted in Emmeline, Sylvia, Christabel, Roach Court and

Thomas Court blocks. Photographic and location details of the apartment blocks are shown in 14 Appendix 4. The heat-providing systems are described in Chapter 4.

3.2.5 Scenario analysis (3)

Scenario analysis of possible future pathways for electrification of heat has been considered as part of this research. For these purposes, several scenarios have been developed up to 2050, driven by the UK's carbon reduction targets (DECC, 2008; Strachan and Kannan, 2007; UKERC, 2009a; UKERC, 2009b).

Several studies have recently been performed that are related to low carbon and future energy demand in the UK, (DEFRA, 2007b; ICEPT and CES, 2010; UKERC, 2009a). The Government is also producing 'route maps' towards a decarbonised energy system through its Low Carbon Transition Plan (DECC, 2009c) and the Carbon Plan (HMGOV, 2011). Some of the scenarios that these studies consider have common characteristics with this research, such as those that include the electrification of domestic heating.

This research considers both energy supply scenarios that can achieve the carbon reductions targets but also take into account the implications of a 'business-as-usual' approach, demand reduction through energy efficiency measures and an 'all-electric' future. Seven scenarios are studied and compared using the timeframe of 2010 to 2050:

- *Reference-national* – business-as-usual.
- *High electricity* – based on high degree of electrification of heat.
- *National Grid* – takes a more moderate approach to electrification of heat.
- *Markal* – common approach to heat through district heating and heat pumps.
- *Reference-urban* – business-as-usual but at the urban level.
- *Urban One* – major move towards domestic electrification of heat.
- *Urban Two* – change in domestic heat through community based heat systems.

The scenario analysis has involved the following stages:

- *Provision of data* - output data from the environmental, techno-economic and social assessments for each heat providing system are consolidated ready for integrated analysis using spreadsheets.
- *Electricity generation data* – the *SPRIng* scenarios and tools (Spring, 2011a) are used to calculate the LCA impacts of electricity generation and supply over the selected scenario period. *SPRing* is a spreadsheet based tool that calculates impacts based on the generation mix.
- *Pathways calculator* – the *Pathways* 2050 calculator (DECC, 2012a) provides a framework of energy supply scenarios (including the four selected national scenarios) and includes population data, domestic heating data, and energy demand data. Pathways calculator is a tool and model that enables the creation of UK emissions reduction pathways using real UK data. The data from the calculator is refined and processed ready for integrated analysis.
- *Integrated analysis* – the data from the sustainability assessments, electricity generation, and pathways calculator are integrated into a common spreadsheet model for each of the selected scenarios.
- *MCDA* – the *Onbalance* MCDA software provides a ranking of scenarios according to cumulative impacts up to 2050 and comparative impacts between the year 2010 and 2050.
- *Results* – interpretation of the results.

3.2.6 Multi-criteria decision analysis – (MCDA) (4)

Multi-criteria decision analysis has been used to assess the eight heat-providing systems for domestic heating in cities using the buildings discussed in section 3.2.4 as case studies. MCDA facilitates decision making where there is a complexity of issues or a wide range of criteria. MCDA helps to aggregate these criteria into a single number to aid decision-making.

In this work, the MCDA analysis has been carried out using the software *OnBalance* (Quartzstar, 2010) which is based on a Multi-attribute utility/value theory

(MAUT/MAVT) approach (Linkov and Ramadan, 2004). As indicated in Figure 17, the MCDA process has involved six steps: identification of criteria, score consolidation, normalisation of scores, criteria weighting, MCDA and results evaluation; these are outlined briefly below.

- *Identification of criteria* – in this stage, decision criteria to be used within the MCDA process have been identified and they comprise the environmental impacts obtained through LCA, life cycle costs obtained via LCC and social aspects identified through the online survey and interviews of stakeholders.
- *Consolidation of criteria scores* – the criteria and associated data are placed and consolidated within three headings - Environmental, Techno-economic and Social for use in the MCDA modelling.
- *Normalisation* – the data for each of the criteria are normalised against the maximum for that criterion – this has been performed using spreadsheets developed in this work.
- *Weighting of criteria* – weight is applied to each criterion within the MCDA software to indicate its relative importance to the overall evaluation – this is conducted as input weight and % weight. The MCDA considers i) equal weighting of all criteria, ii) importance of environmental criteria, iii) importance of techno-economic criteria, and iv) importance of social criteria. In this research, the weights have been defined by the author of this work, as it was outside the scope of the research to consult the stakeholders on these. Different weights have also been explored through sensitivity analysis.
- *Preference orders* – describes the robustness process that ranks the criteria of the best performing system against other systems. This enables further sensitivity analysis to be conducted against the highlighted criteria.
- *MCDA* – the multi-criteria decision processing is conducted using software called *OnBalance* (Quartzstar, 2010). *OnBalance* provides a basic framework for MCDA and presentation of results (FEI, 2013; Quartzstar, 2010).
- *Results* – the results from the MCDA are presented using graphs generated by the software.

3.2.7 Results and recommendations (5)

The results and recommendations from this research aim to provide stakeholders such as government, developers, and utilities with the tools to assess the sustainability of energy provision to urban dwellings. They also serve to inform the users on the sustainability of different heat-providing systems.

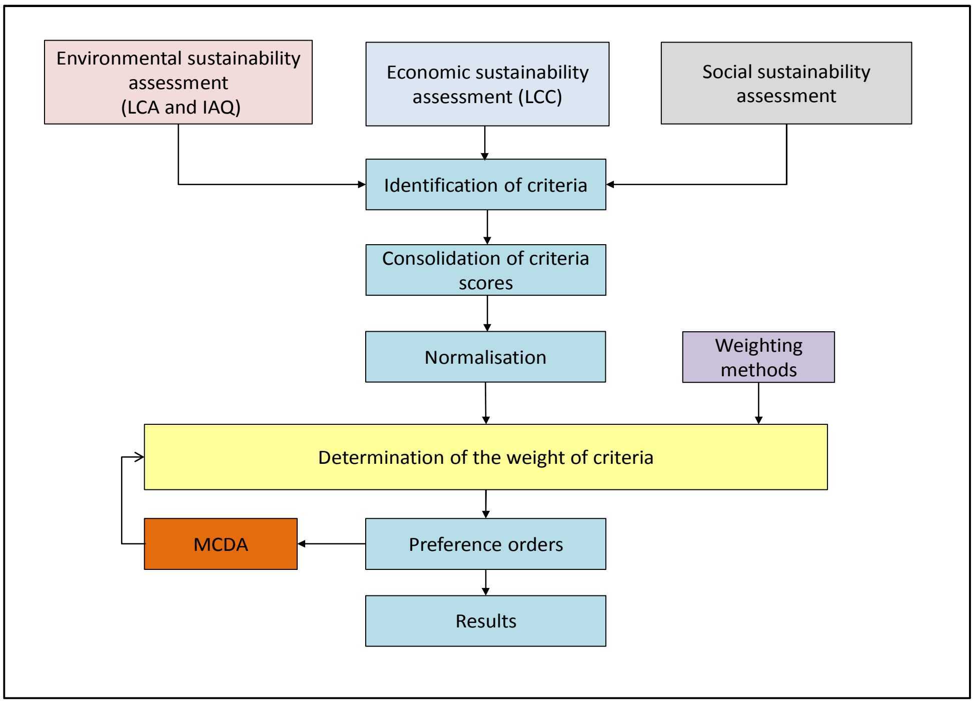


Figure 17 MCDA process for electrification of heat.

3.3 Summary

The methodology described in this chapter uses a life cycle approach, taking into consideration the environmental, techno-economic and social sustainability issues of case studies in the context of the electrification of heat. The subsequent multi-criteria decision analysis and scenario analysis compare and contrast sustainability for a range of stakeholder concerns for residential heat supply in cities. By taking a life cycle approach, heating-providing systems, including all-electric systems are considered on an equivalent basis.

The following chapters, starting with environmental sustainability, discuss the application of sustainability assessment approaches.

4. Evaluation of environmental sustainability

4.1 Evaluation of environmental sustainability: Life cycle impacts

The evaluation of environmental sustainability of the systems providing space, water and cooking heat has been conducted using life cycle assessment (LCA) and air quality monitoring (AQM). The results obtained from LCA are used to estimate and compare the life cycle environmental impacts of the different systems while the results of AQM are used to determine direct air emissions and related environmental impacts in the indoor environment that may be associated with these systems. This chapter focuses on the life cycle impacts and the subsequent on the direct impacts.

4.1.1 Goal and scope of the LCA study

The goal of this LCA study has been to:

- estimate and compare the environmental impacts of the eight heat providing systems considered here; and
- identify the life cycle stages that contribute the most to the environmental impact to help identify opportunities for improvements.

The study is based in the UK. The scope of the study is from 'cradle to grave', considering the extraction of raw materials, manufacture of the system components such as boilers, panels, pumps and storage cylinders, their transport and installation, maintenance, operation and end of life management (e.g. disposal and recycling). This is depicted in Figure 18.

4.1.1.1 Functional unit

The functional unit is defined as the 'supply of 59,569 GJ over 40 years (or 16.3 GJ/m^2 over 40 yrs.) of heat energy for space and water heating and cooking, reflecting the demand for typical one- and two-bedroom apartments which represent the majority of apartments in the UK (Nationwide, 2008). The period of 40 years is assumed to correspond to the scenario timeframes (up to 2050) considered in this work. Typical apartment occupancy assumed is based on the Standard Assessment Procedure (SAP) which takes into account the size of the building and standard heating demand hours

(DECC, 2011d). The overall energy consumption is estimated using SAP 2005 design data and guidance (BRE, 2009a), information from individual residents, technical details of the installed and modelled systems and reference to average consumption calculations and patterns from UK flats and apartments of a similar size and occupancy. Table 9 shows the studied systems and the energy type used for each system: space, water and household cooking.

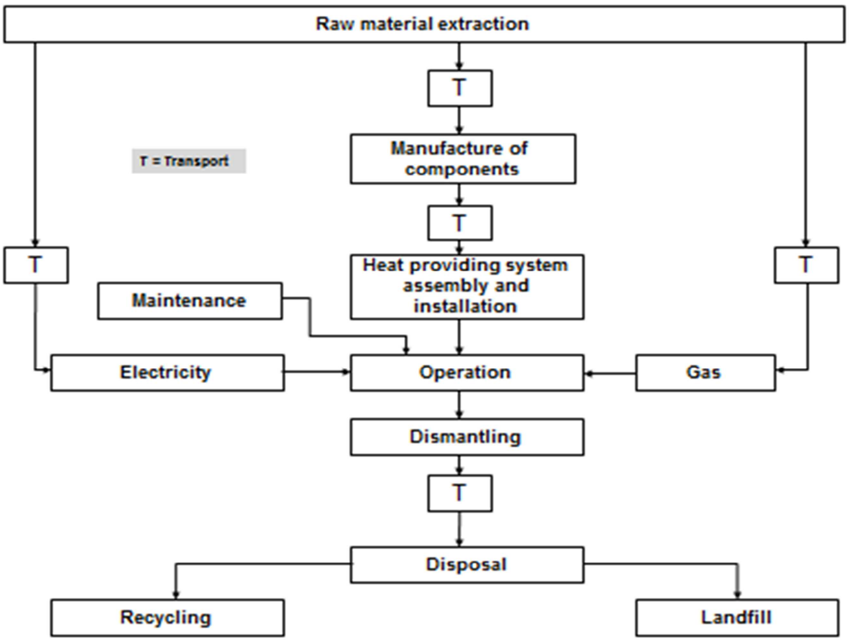


Figure 18 Life cycle flow diagram of the studied heating and cooking systems.

Table 9 Energy type use.

System type	Space heating	Water heating	Cooking
Electric panel	Electricity	Electricity	Electricity
Electric storage	Electricity	Electricity	Electricity
Air-source heat pump (ASHP)	Electricity	Electricity	Electricity
Gas boiler	Gas	Gas	Gas
Combined gas and electric	Electricity	Gas	Electricity
District heating	Heat from gas	Heat from gas	Electricity
Combined heat and power	Heat from gas	Heat from gas	Electricity
Combined solar thermal and gas	Gas	Heat from solar thermal	Gas

Table 10 shows the final calculated consumption per apartment and the breakdown of the energy provided by each system. Individual system and equipment efficiencies considered in the calculations have been obtained from literature (detailed throughout this chapter), own calculations and experience. Energy used by microwaves, electric kettles and extractor fans is not included as these are assumed to be approximately the same whatever system is used.

Table 10 Calculation of functional unit.

Energy demand system	Energy consumption per apartment (kWh/m^2 yr.)[a]	Energy consumption per apartment (kWh yr.)[b]	Number of apartments per block[c]	Floor area m^2	Total demand (GJ 40 yr.)
Space heating	59		62	$55m^2$ one-bedroom & $62.5m^2$ two- bedroom apartments	29,863
Water heating	50		62		25,308
Cooking (average):		509	62		4,544
				Total (GJ 40yrs)	59,569

[a] Energy demand per system per annum (kWh/m^2 yr.) and comparison with other system data:

	Average UK (kWh/m^2 yr) (Monahan and Powell, 2010)	New build (kWh/m^2 yr) (Lazarus, 2003)	Average for typical flats (kWh/m^2 yr) (Henderson and Young, 2008)	Manchester apartment blocks (kWh/m^2 yr)
Domestic hot water (DHW)	103	78	55	50
Space heating (SH)	140	59	79	59

[b] Cooking technology ownership and consumption per year (MTP, 2007):

	Ownership (% households) (2011)	Typical consumption (per use) [delivered energy] kWh	Typical number of times used per year per cooking type	Total energy consumption for cooking (kWh yr based on an average apartment)	Average per apartment (kWh yr)
Electric oven	64%	0.96	135 (yr 2007)	130	
Electric hob	45%	0.71	424	301	509
Gas oven	35%	1.52	as per electric oven	205	
Gas hob	55%	0.9	424	382	

[c] 48 one-bedroom apartments and 14 two-bedroom apartments.

4.1.1.2 Assumptions and limitations

The main assumptions for the studied systems are as follows:

- The systems under study are those commonly used for urban housing in the UK.
- The systems are suitable for use in one- and two-bedroom apartments.
- One-bedroom apartments have a floor area of approximately 55 m^2 and two bedroom apartments 62.5 m^2.
- The systems are assumed to be operational for a 40 year period.
- The apartment buildings considered in the study have on 62 apartments – this is the average found during the Manchester city apartment study (Sims, 2011) – see 15 Appendix 5. There are typically 48 one- and 14 two-bedroom apartments in each building.

- The boundary of each heat-providing system is defined as the point of entry of the main gas service pipe or electric cable into the apartment block and is considered as the place where the supply to the block can be physically isolated.
- All systems are installed and operated according to the Domestic heating compliance guide (CaLG, 2008a), building regulations 2006 (ODPM, 2006b; ODPM, 2006c) and provide adequately the heating and cooking demand as stated previously.
- Hot-water systems assume showers use a thermostatically controlled mixer unit without the need for a booster pump.
- The individual hot-water supply network to taps etc. has not been considered as this is the same for each of the selected systems.
- Energy consumption pertaining to appliances (other than cooking), lighting and other general uses are not considered here as they are assumed again to be the equal for all systems.
- Replacement of individual equipment and components is taken into account according to CIBSE indicative life expectancy factors (CIBSE, 2008; CIBSE, 2010b). It is assumed that an appliance or component, at the end of its life, is replaced with another of the same efficiency and design - thus, the effect of any technological advances in system or component designs is not considered.
- The steel and iron, copper, aluminium, zinc and nickel components are recycled according to current UK recycling rates of 65%, 80% and 40% respectively (DEFRA, 2010).

4.1.2 Inventory data

The primary data for the systems given in Table 11 and in Table 12 have been collected for the components and parts of each system considering technologies, fuels, life expectancy, efficiency, service intervals and overall use. The sources of these data are manufacturers, literature and own calculations – a detailed list of sources are shown in 16 Appendix 6. Basic research was carried out by the Author through the disassembling of the individual technology components and subsequent weight measurement of the various materials. The background LCA data comes from the *EcoInvent* database (EcoInvent, 2008).

Table 11 System type showing service life, efficiencies and service intervals.

[(CIBSE, 2008; CIBSE, 2010b; Sedbuk, 2010)].

System type	System components	Life expectancy (Years)	Efficiency (where applicable)	Service intervals	Other energy uses
Electric panel	Electric panel heaters Electric towel rail Immersion heaters Water storage cylinder Electronic controllers Common electric system In house electric wiring Electric meter installation	8 8 10 25 10 30 30 20	100% 100% 100%	5 yearly for panels and annually for water storage tanks	Electric hob Electric oven
Electric storage	Electric storage heaters Other items as per electric panel system	20	98%	As per panel system	Electric hob Electric oven
Air source heat pump	Common supply system Wet heating system Air source heat pump unit	10 40 15		Annually for ASHP	
Gas boiler	Combination gas boiler Wet heating system Radiators System pump Electronic controllers Common gas pipe Gas meter installation Circulating pumps	10 40 15 15 10 25 20 10	89.1% SH & 67% DHW 85%	Annually for gas boilers	Gas hob Gas oven Boiler power Water pumping
Combined gas and electric	Centralised water boilers Common hot water system Electric panel heaters Electric towel rail Electric meter installation	15 30 8 8 20	85%	Annually for gas and 5 yearly for electric	Electric hob Electric oven Common gas boiler power Centralised water pumping
District heating	Centralised gas boilers Pumping system Heat exchangers Distribution pipes Heat stations Other components as per gas boiler system	15 20 25 25 10	5% of total supplied heat taken as network losses	Annually for centralised boilers	Electric hob Electric oven Water pumping Heat station control
Combined heat and power	Combined heating and power unit Other components as per district heating system	15		Annually for centralised boilers and CHP unit	Electric hob Electric oven Water pumping Heat station control
Combined solar thermal and gas	Solar thermal panels Common solar water supply system Apartment solar thermal control module	25 30 10		Annually for solar thermal system	Gas hob Gas oven Boiler power Water pumping Apartment module control

Table 12 Main materials used during the 40 years of apartment block use – electric and gas systems.

System type **System components**	**Materials**	**Electric panel system [kg]**	**Electric storage heater system [kg]**	**ASHP system [kg]**	**Gas system [kg]**	**Combined system [kg]**	**District heating [kg]**	**Community combined heating & power system [kg]**	**Combined solar thermal and gas [kg]**
Electric panel heaters	Steel:	4,880	n/a	n/a	n/a	4,880	n/a	n/a	n/a
	Copper:	150				150			
	Magnesium oxide:	100				100			
	Aluminium oxide:	100				100			
	Glass fibre:	100				100			
	Polyethylene:	200				200			
	Corrugated board packaging:	300				300			
	Packaging film:	200				200			
	Powder coating:	787m^2				787m^2			
Electric towel rail	Steel:	3,100	3,100	n/a	n/a	3,100	n/a	n/a	n/a
	Corrugated board packaging:	93	93			93			
	Powder coating:	155m^2.	155m^2			155m^2			
Immersion heaters	Steel:	74	74	74	n/a	n/a	n/a	n/a	n/a
	Copper:	27	27	27					
	Chromium steel:	496	496	496					
	Magnesium oxide:	99	99	99					
	Brass:	50	50	50					
	Polyethylene:	50	50	50					
	Corrugated board packaging:	99	99	99					
	Packaging film:	25.	25.	25.					
Water storage cylinder	Copper:	348	348	348	n/a	n/a	348	348	348
	Chromium steel:	3,000	3,000	3,000			3,000	3,000	3,000
	Brass:	100	100	100			100	100	100
	Polyurethane:	300	300	300			300	300	300
	Corrugated board packaging:	300	300	300			300	300	300
	Powder coating:	30m^2.	30m^2.	30m^2.			30m^2.	30m^2.	30m^2.
Electronic controllers	Aluminium cast alloy:	156	96	156	60	132	13		85
	Acrylonitrile-butadiene-styrene:	207	192	207	90	159	20		
	LCD module:	16	11	16	6	14	1.5		5
	Corrugated board packaging:	468	468	468	180	395	38		
	Steel:						1.6		
	Copper:								11

Common electric system	Steel:	602	602	602	n/a	602	n/a	n/a	n/a
	Copper:	1 282	1 282	1 282		1 282			
	Aluminium:	426	426	426		426			
	Powder coating:	65 m^2.	65 m^2.	65 m^2.		65 m^2.			
In house electric wiring	Copper:	755	755	755		755			
	Brass:	31	31	31		31			
	Polyvinylchloride:	62	62	62		62			
	Urea formaldehyde:	93	93	93		93			
	Corrugated board packaging:	62	62	62		62			
	Packaging film:	37.	37.	37.		37.			
Electric meter installation	Copper:	72	72	72	n/a	72	n/a	n/a	n/a
	Polycarbonate:	25	25	25		25			
	Ceramic tile:	12	12	12		12			
	Corrugated board packaging:	37.	37.	37.		37.			
System installation	Steel:	65	65	111	220	131	244	244	340
	Polyethylene:	33	33						
	Polycarbonate:	248	248						
	Polystyrene:	40	40	70	80	93	105	105	150
	Cement mortar:	133	133	378	469	452	659	659	810
	Polypropylene:			155	620				
	Polyvinylchloride:			62	248	248	248	248	448
	Brass:			30		40	45	45	30
	Copper:				12				
	Excavation:						360 m^3	360 m^3	
Maintenance	Iron-nickel-chromium alloy:	25	25	0.8		13			
	Magnesium oxide:	50	50	1.6		25			
	Aluminium oxide:	50	50	1.6		25			
	Ceramic tiles:	25	25						99
	Corrugated board packaging:	50	50	64	99	27			161
	Packaging fleece:	25	25	63	99	13	62	62	50
	Bronze:			31	50		37	37	11
	Tetrafluoroethylene:			2	3		3	3	
	Steel:					16	48	6048	16
	Copper:			31		8	34	34	8
	Bronze:					2			
	Ceramic tiles:					13			
	Synthetic rubber:						31	31	
	Polyethylene:						100	100	
Combination gas boiler	Steel:	n/a	n/a	n/a	5,828	n/a	n/a	n/a	5,828
	Copper:				174				174
	Brass:				124				124
	Aluminium:				74				74
	Rock wool:				248				248

	Polyethylene: Synthetic rubber: Zinc coating: Powder coating: Corrugated board packaging:				99 50 248 m^2 184 m^2 74.				99 50 248 m^2 184 m^2 74.
Wet heating system	Steel: Copper: Cast iron: Brass: Tube insulation elastomere: Packaging film: Powder coating: Zinc coating:	n/a	n/a	24,370 2 618 155 1,254 443 1,600 m^2 62m^2.	12,206 2 618 155 1,254 443 1,458 m^2 62m^2.	n/a	12,206 2 618 155 1,254 443 1,458 m^2 62m^2.	12,206 2 618 155 1,254 443 1,458 m^2 62m^2.	12,206 2 618 155 1,254 443 1,458 m^2 62m^2.
Common gas pipe	Steel: Copper: Magnesium oxide: Brass:	n/a	n/a	n/a	1,786 180 20.	717	717	717	1,786 180 20.
Gas meter installation	Steel: Copper: Brass: Aluminium: Polyethylene: Powder coating:	n/a	n/a	n/a	304 81 81 25 37 39m^2.	n/a	n/a	n/a	304 81 81 25 37 39m^2
Protection fluid	Tap water: Boric acid: Triethanolamine: Benzo[thia]diazole- compounds:	n/a	n/a	4,600 0.23 	12,400 124 248 62		13,000 260 65	13,000 260 65	40,000 2,000
Centralised water boilers	Steel: Copper: Chromium steel: Brass: Aluminium: Rock wool: Polyethylene: Synthetic rubber: Zinc coating: Powder coating:	n/a	n/a	n/a	n/a	774 107 587 80 96 80 27 5 53 m^2 28m^2.	2,295 180 990 135 162 135 45 9 90 m^2 47 m^2.	2,295 180 990 135 162 135 45 9 90 m^2 47 m^2	n/a
Common hot water systems	Steel: Copper: Brass: Aluminium: Rock wool:	n/a	n/a	227 606 24	n/a	815 339 80 345	815 339 80 345	815 339 80 345	 606 24 345

	Tube insulation elastomere: Polyethylene:			 40		222 40	222 40	222 40	221
Electric storage heater	Steel: Copper: Magnesium oxide: Aluminium cast alloy: Glass fibre: Polyethylene: Ceramic tiles: Corrugated board packaging: Powder coating:	n/a	4,500 80 40 40 40 400 100 120 1,012m^2.	n/a	n/a	n/a	n/a	n/a	n/a
ASHP unit	Steel: Copper: Brass: Aluminium: Powder coating: Cast iron:	n/a	n/a	2,961 1,029 273 1,617 168 m^2 105	n/a	n/a	n/a	n/a	n/a
Refrigerant	Hydrogenflouride: Chlorine: Triethanolamine:	n/a	n/a	83 38 66	n/a	n/a	n/a	n/a	n/a
Pumps, expansion devices and tanks	Steel: Polyethylene: Brass: Chrome steel: Stainless steel:	n/a	n/a	1,488 25 248 87	n/a	n/a	0.8 1.6 48	0.8 1.6 48	282 6
Heat stations	Steel: Copper: Brass: Chrome steel: Powder coating: Polyethylene: Synthetic rubber:	n/a	n/a	n/a	n/a	n/a	1,856 335 378 620 124 14 65	1,856 335 378 620 124 14 65	n/a
Distribution pipes	Polyethylene: Steel: Copper: Insulation:	n/a	n/a	n/a	n/a	n/a	572 613 255 166	572 613 255 166	n/a
Solar collectors	Brass: Steel: Copper: Aluminium: Polyethylene:	n/a	n/a	n/a	n/a	n/a	n/a	n/a	50 810 610 4,810 10
CHP unit	Steel: Chromium steel:	n/a	n/a	n/a	n/a	n/a	n/a	6,336 800	n/a

	Copper: PVC: Polyethylene: Cast iron: Rock wool:							22 15 157 2,000 960	

4.1.3 LCA modelling and impact assessment

GaBi LCA software V4.4 (PE, 2010) has been used for system modelling and the environmental impacts estimated using the CML 2 Baseline 2000 methodology (CML, 2001). The following impacts are considered:

Abiotic resources - elements (ADP elements)	kg Sb eq.
Abiotic resources - fossil fuels (ADP fuels)	GJ.
Acidification potential (AP) (SO_2, NO_x, HCL, and NH_3 emissions)	kg SO_2 eq.
Eutrophication (EP) (N, NO_x, NH_4+, PO_4^{3-} etc.)	kg PO_4^{-3}.
Freshwater aquatic eco-toxicity potential (FAETP)	kg DCB eq.
Global warming potential (GWP) (GHG emissions)	kg CO_2 eq.
Human toxicity potential (HTP) (excluding radiation)	kg DCB eq.
Marine aquatic eco-toxicity potential (MAETP)	kg DCB eq.
Ozone depletion potential (ODP) (CFC, halogenated HC emissions)	kg R-11 eq.
Photochemical smog creation potential (VOCs and NOx) (POCP)	kg C_2H_4 eq.
Terrestrial eco-toxicity potential (TETP)	kg DCB eq.

The following sections first describe each system in turn detailing the technologies, energy supply and system requirements that provide and support space, water and cooking heat for households. This is followed by the discussion of the impacts of each system.

4.1.4 Electric panel system

The electric panel system considered in this work is an all-electric system that uses electricity from the UK national grid for both space and water heating as well as for cooking. Such a system is a popular option for apartment blocks in the UK (Myers, 2004) and the one considered here is based on that installed in the *Emmeline* apartment block in Manchester. This system is typified by immediate space heating availability and the storage of hot water. The life cycle of the installed 'electric panel system' is depicted in Figure 19 with the system schematic shown in Figure 20. The system is described in more detail below. The inventory data are given in Table 10 -
Table 12.

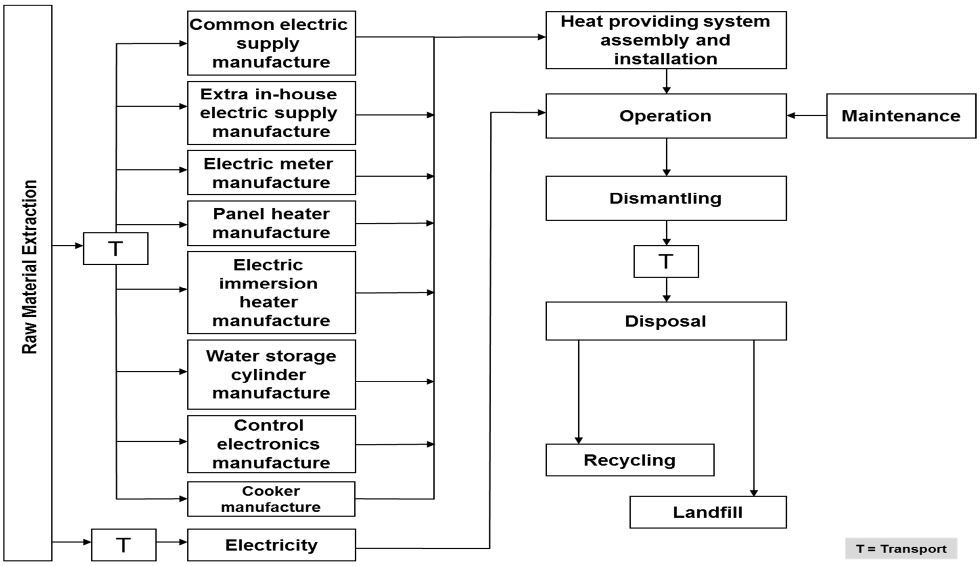


Figure 19 Life cycle flow diagram of the electric panel system used for space and water heating and cooking.

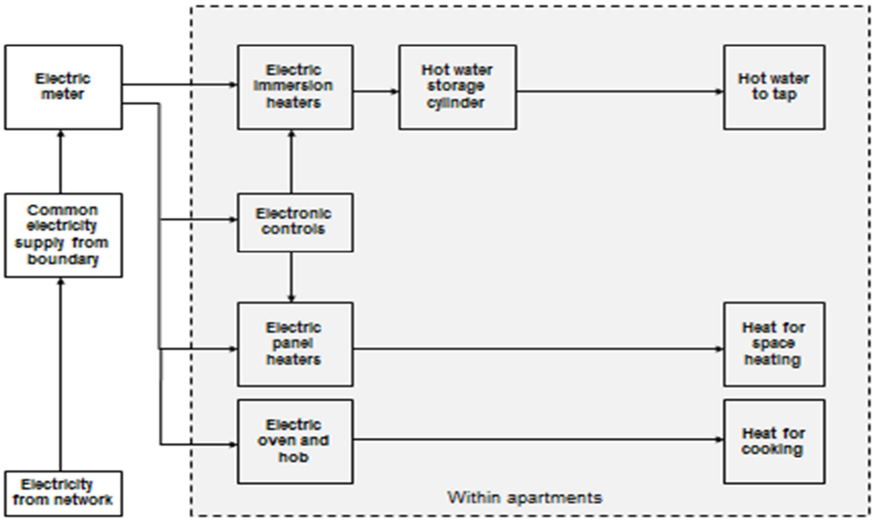


Figure 20 Schematic diagram of the electric panel heating and cooking system.

4.1.4.1 System description

Space heating: This is provided through the use of wall mounted *NOBO* electric panel heaters rated at either 1,000 Watts or 1,500 Watts each and function by passing an electric current through a resistive element that generates heat (ENER, 2010). The panel heaters are manufactured from a steel frame and sheet cover that is powder-coated derived using polyester/epoxy hybrid material (Interpon, 2013) and vented at the top and bottom. Heating elements placed within each panel are surface-ribbed with aluminium fins to increase heat transfer rates. An integrated electronic circuit programmer provides heat and time control for each panel via an LCD display and switch. An oil-filled electric steel towel rail provides heat in the bathroom.

Water heating: Hot tap and shower water heating takes place by two 3,000 Watt electric immersion heaters - one for main water heating and the other for topping up. The elements are manufactured from copper. Elements are placed within an *OSO* insulated direct acting water storage cylinder of either 125 or 175 litre capacity. This is manufactured from stainless steel with an outer steel powder-coated casing and insulation placed in-between. Ancillary equipment to the water cylinder includes: water valves made from plastic and brass and a wall mounted electronic programmer that provides heating time/temperature control. Finally, copper pipes provide connections to the cold water supply and hot water outlet system.

Cooking: An electric hob and oven are assumed here for cooking purposes. However, unlike the water and space heating systems, the hob and the oven components and construction are not considered in the LCA study; only the energy supply.

Energy supply system: It is assumed that each apartment block has its own separate energy supply system that is connected to the local electricity network. Grid electricity is typically provided to an 800 kVA transformer situated on the ground floor of the apartment block providing 415 Volts to a bus-bar or similar cabling system. Electricity at 240 Volts is then supplied to apartments through bus-bar tap-off connections or cable junctions; this is then isolated and metered close to or within each apartment. Where individual apartment space heating and hot water are supplied solely by electricity, incoming cables are rated at 8 kVA; otherwise standard cables of 1.5 kVA capacity are installed - 3 kW per apartment with gas heating or 7.5 kW per apartment with all electric cooking and heating (BSRIA, 2011). Cables and transformers generally need to be increased in size to accommodate the elevated electricity demand and peaks of electric only heating and this is considered here both for common mains wiring and in-apartment wiring.

Installation: This includes wall hanging and wiring in of heaters, the provision and fixing of the apartment heating electric wiring and the fixing and support of the main electric feeder cables and block switches back to the supply transformer. Provision is also made for the piping of hot water storage cylinders and the immersion heaters electrical connections.

Transportation: The electric panels are transported from Northern Ireland and water heating units from the manufacturing site in Norway. Both panels and units are transported by ship and on the mainland by lorry to the installation site.

Maintenance: This consists of inspection, service and maintenance. Common supply systems to each apartment such as electricity and cold water are maintained by the relevant utilities. There are no legal requirements for systematic electric heating maintenance, however good practice indicates that inspection checks should be conducted at least on a five yearly basis for space heating and annually for water storage tanks[5].

Disposal: The electric panels, hot water cylinder and immersion heaters are removed from the apartment, transported and made available for recycling. Electric wiring and bus bar systems would follow the same process.

4.1.4.2 Impact assessment

The LCA results for the electric panel system are shown in Figure 21. For example, the total GWP is estimated at 11,449 tonnes CO_2 eq. over 40 years which is mainly due to the electricity used – the GWP of the latter is equal to 11,324 tonnes over 40 years or 73.6 kg CO_2 eq./m^2 yr. This compares to Henderson and Young (2008) who found that using electric panel heating and immersion heaters produced 46.61 kg CO_2 eq.m^2 yr. from operational energy alone. The study was based on apartments with similar floor areas but using the SAP 2005 system (BRE, 2009a) for calculation and not CO_2 equivalents.

[5] Based on requirement to regenerate the internal air gap within water storage cylinder.

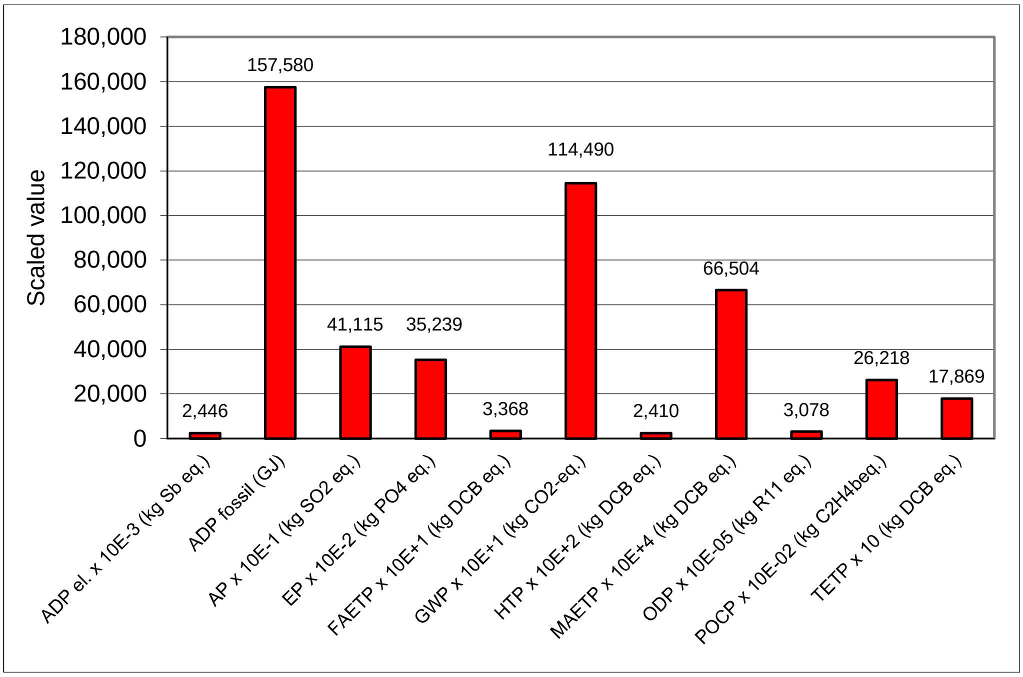


Figure 21 Life cycle environmental impacts for the electric panel system over a 40 year period.

[All values over 40 years. The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets]

The contribution of different life cycle stages to each impact is shown in Figure 22 indicating that operational electricity contributes to over 65% of all impacts. The next largest contributor are the raw materials used and their manufacture into the system components contributing around 35% of the ADP element impacts, and in particular related to hot water storage cylinders, electric panel heaters and the individual panel electronics – see Figure 23. This is largely due to the use of stainless steel in the storage cylinder which contributes 70.9% of the TETP, 61.5% of the HTP and 52.4% of the FAETP from the system components. Furthermore, electric heating panels cause 33.5% of ADP fossil, 28.6% AP, and 28.1% of POCP from the system components, again owing to the life cycle impacts of steel.

Heating control electronics contribute 38.4% of ADP- element and 27.6% of the GWP. The former is due to the depletion of gold, tellurium, and silver and the latter due to the CO_2 emissions during the manufacture of the components and circuit board. Other impacts are associated with the small LCD screen commonly found on programmers and controllers.

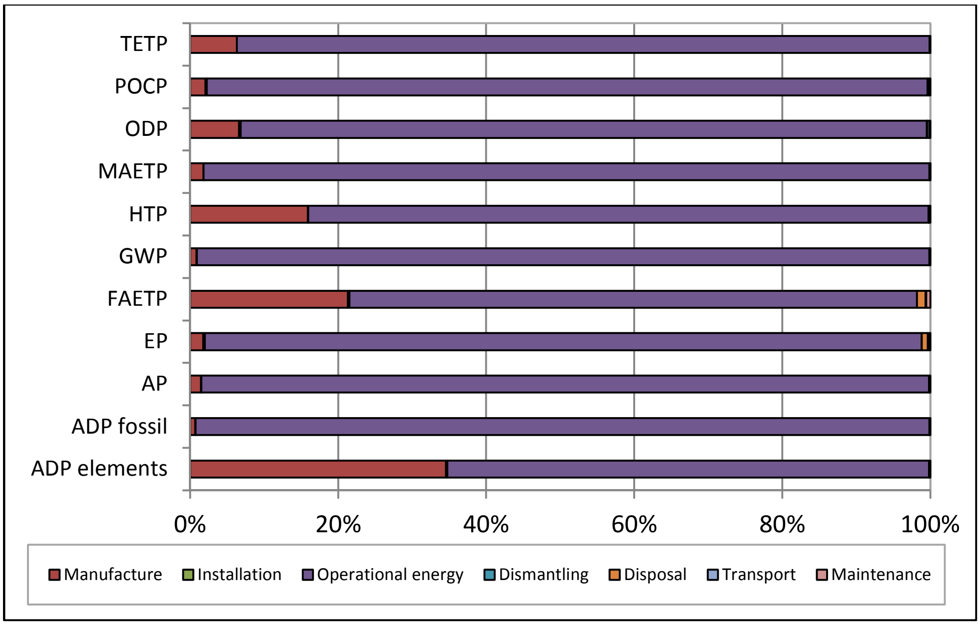


Figure 22 Contribution analysis for the electric panel system (incl. operational energy) over a 40 year period.

[Raw materials and manufacture are combined].

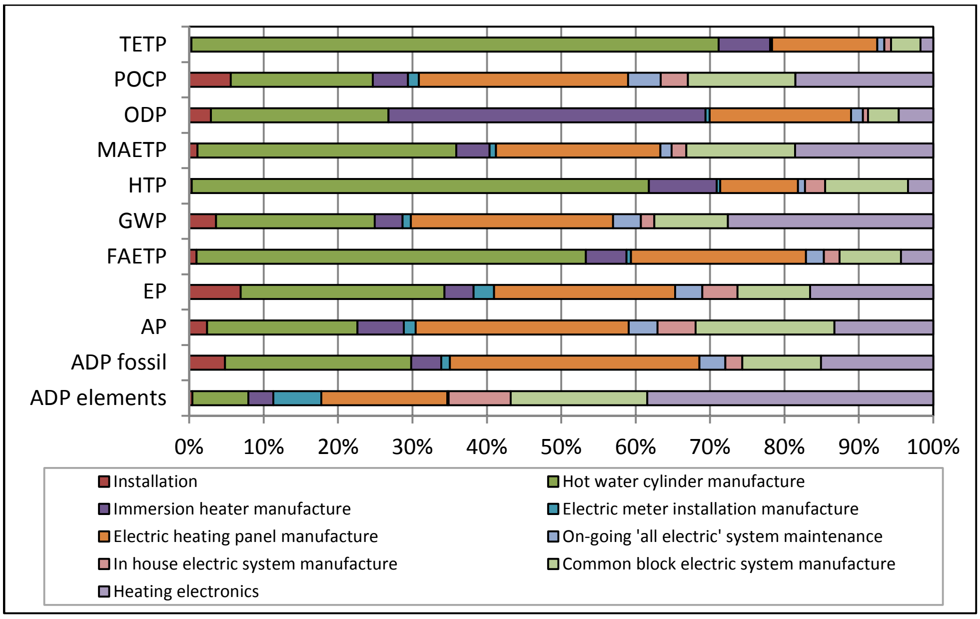


Figure 23 Contribution analysis for the electric panel system (operational energy removed) over a 40 year period.

4.1.5 Electric storage system

The electric storage heating is installed in the *Thomas Court* apartment block and as per the panel system; this can be considered an all-electric system. It consumes off peak and standard electricity from the UK national grid for cooking and both space and water heating by storing heat for use later. The life cycle of the installed 'electric storage system' is depicted in Figure 24, with the system schematic shown in Figure 25. The system is described in more detail below. The inventory data are given in Table 10 - Table 12.

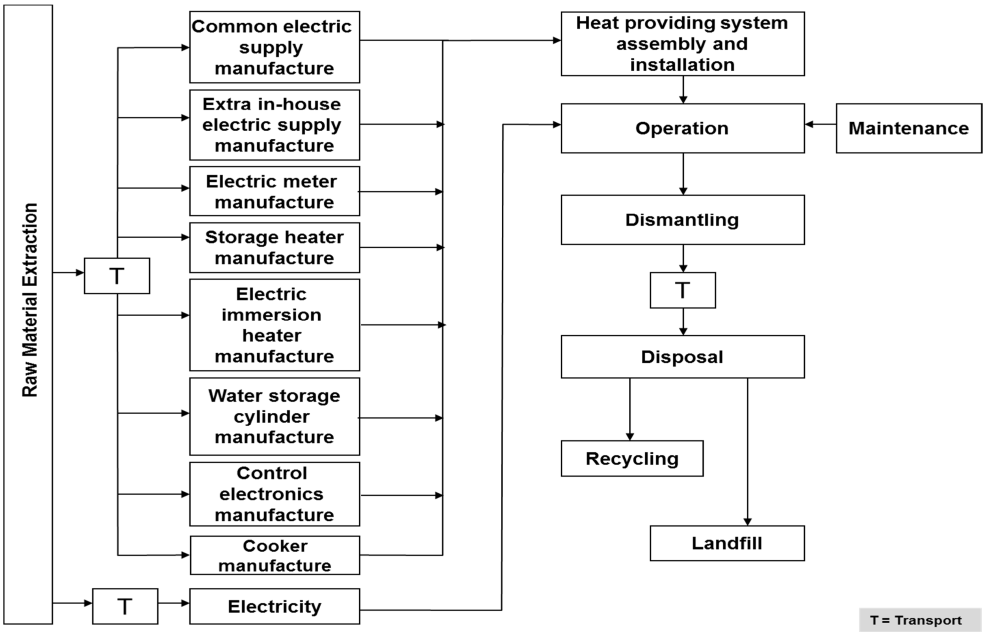


Figure 24 Life cycle diagram of the electric storage system for heating and cooking.

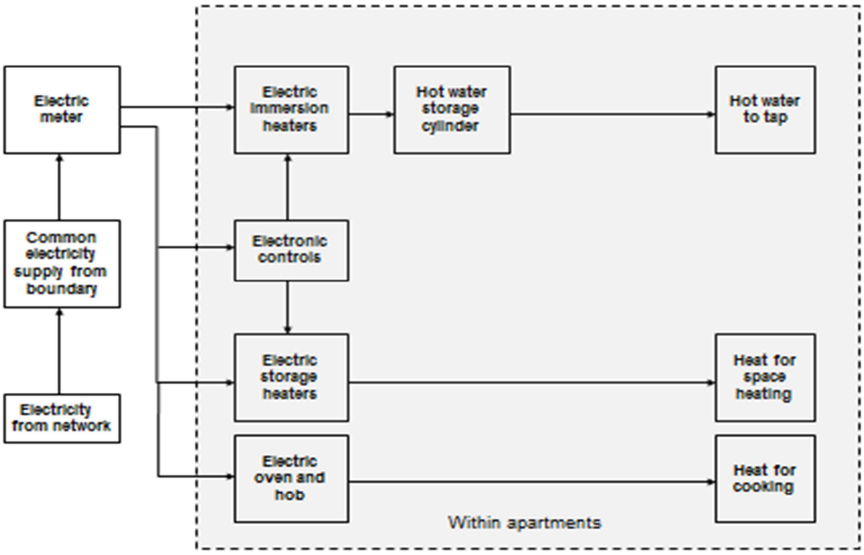


Figure 25 Schematic diagram of the electric storage system for heating and cooking.

4.1.5.1 System description

Space heating: This is provided through the use of *Dimplex Duoheat* 300i or 400i electric storage heaters that are floor mounted and have a rating of either 3,000 or 3,500 Watts depending on their location within the apartment. The storage heaters are made from a galvanised steel frame, steel sheet cover that is vented at the top and powder coated throughout. Heating elements are placed within each heater and surrounded by vertical bricks. The heat from elements is stored in the bricks because of their low cost and high specific heat capacity (ENER, 2010). Further insulation around the sides of the bricks and steel cover prevents heat leakage horizontally but allows heated air to flow through the top of the heater unit and out into the room. An integrated electronic circuit programmer provides heater charging control for each panel via an LCD display and switch. An oil filled electric steel towel rail also provides heat in the bathroom. Each heater has a separate electricity circuit back to the consumer control unit and meter that provides for off-peak and standard electricity heating control.

Water heating: Hot tap and shower water heating takes place following the method described earlier for the panel system.

Cooking: As only electricity is available within the block, cooking is by an electric oven and hob.

Energy supply system: The electric storage system has an identical supply system to that of the electric panel system. However, additional circuits, wiring and metering facilitate the use of off-peak electricity with households negotiating their own electricity supply contracts; both standard and off peak (economy 7 or 10) electricity.

Installation: This is similar to the electric panel system however, with the installation of additional wiring, sockets and metering to support the off-peak electricity supply.

Transportation: Each of the storage heaters were transported from Northern Ireland by ship and lorry. Hot water cylinders are transported from Norway by ship and then by lorry to the installation site.

Maintenance: Maintenance activities within the apartments are organised and paid for by the apartment owners and landlords. Common supply systems such as electricity and cold water are maintained by the relevant utilities. Inspection checks are conducted as per the panel system.

Disposal: The electric storage heaters, hot water cylinder and immersion heaters are removed from the apartment, transported and made available for recycling. Electric wiring and bus bar systems would follow the same process. The bricks from the storage heaters would be recycled as building material waste.

4.1.5.2 Impact assessment

Results from the LCA analysis are shown in Figure 26; in a similar manner to the electric panel system, the use of operational electricity by the electric storage system has a sizable impact on the environment**.** For example, the total GWP is equal to 12,014 tonnes over 40 years which is due to the electricity used - the GWP impact for electricity use over 40 years is estimated at 11,890 tonnes or 77.4 kg CO_2 eq./m^2 yr. and is particularly evident when using a high carbon electricity mix (DECC, 2010a). This compares to Henderson and Young (2008) who found that electric storage heaters with immersion heaters for hot water produced emissions of 48 kg CO_2 eq./m^2. This system would predominately use off-peak electricity which is available for 7 to 10 hours per day (UKpower, 2010) and draws on base load production capacity that currently includes: nuclear, coal and gas CCGT (Power, 2004).

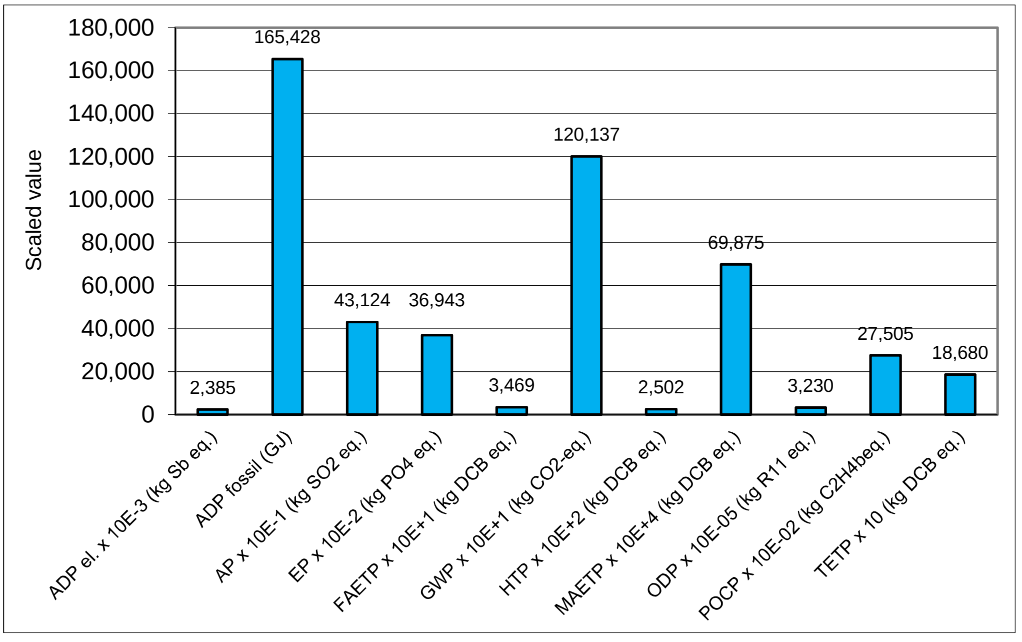


Figure 26 Life cycle environmental impacts for the electric storage system over a 40 year period.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

The contribution of different life cycle stages to each impact is shown in Figure 27 - operational electricity supplied dominates the impacts by contributing to over 70% of all impacts. Further key impacts emerge from raw material extraction for component manufacturing for all indicators, ranging from 1% to 30% of impacts.

Figure 28 shows the contribution of other parts of the life cycle when operational electricity is removed from the results. System components that offer key impacts are similar to the electric panel system including hot water storage cylinders but additionally, the electric storage heaters themselves. The use of stainless steel in the storage cylinder particularly impacts the TETP, HTP and FAETP indicators, offering impact contributions (72.5%, 63.0% and 54.3% respectively). Electric storage heaters exhibit key impacts to the ADP fossil, GWP, EP indicators, offering (32.2%, 30.0% and 26.0% respectively). This is attributable to the steel used in the heater frame and the steel product manufacturing but mainly; the bricks used as the heat store within each heater.

Environmental burdens that arise from brick making are due to air emissions derived from fossil fuel utilization and its energy intensity (Koroneos and Dompros, 2007) and include non-methane volatile organic compounds (NMVOC) to air. Contribution analysis of the life cycle stages therefore show that in addition to the operational electricity supplied over the 40 years, the storage heaters and hot water storage cylinders offer key contributions.

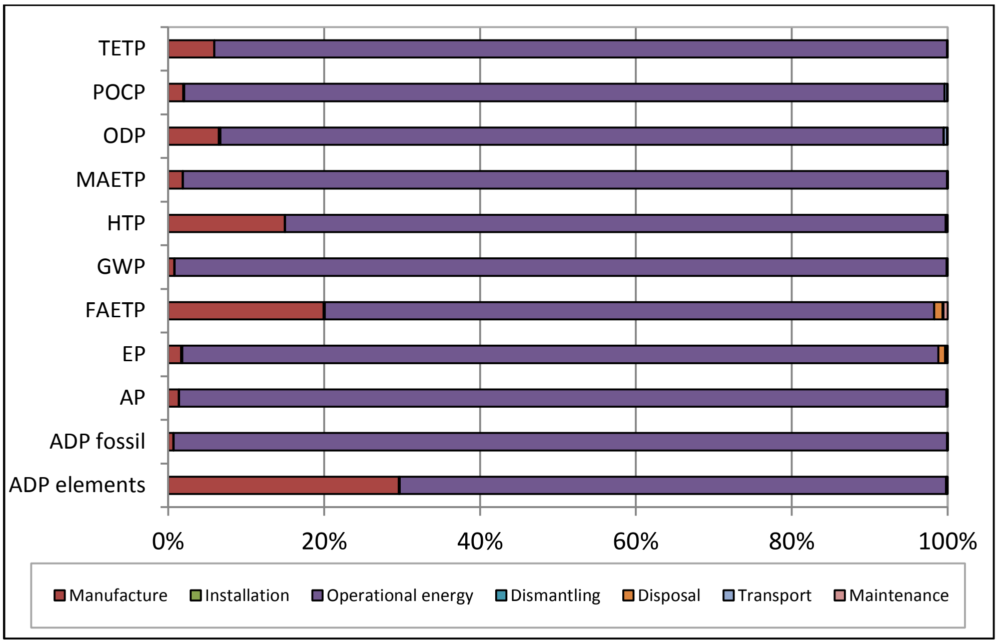


Figure 27 Contribution analysis for the electric storage system (incl. operational energy) over a 40 year period.

[Raw materials and manufacture are combined].

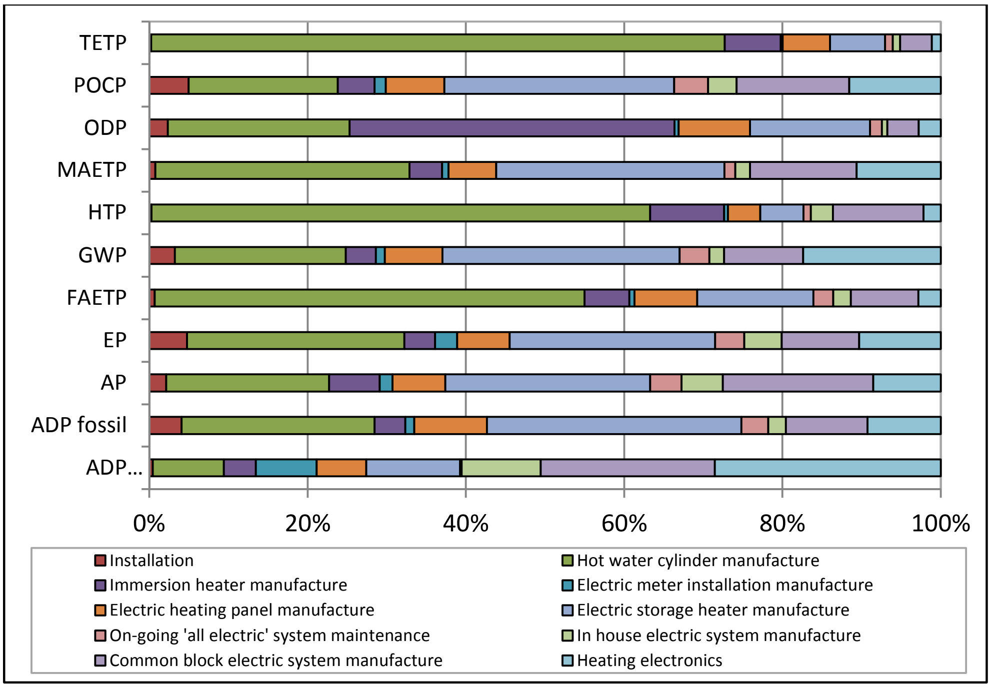


Figure 28 Contribution analysis for the electric storage system (operational energy removed) over a 40 year period.

4.1.6 Air source heat pump system (ASHP)

The community air source heat pump system is installed in the *Friars Wharf* apartment block and consumes electricity from the UK national grid for both space and water heating as well as for household cooking and therefore is also considered as an all-electric system. The system is characterised as being highly efficient using less high grade energy to produce the released heat. In addition, space heating is more measured and heated water is stored for later use. Specific energy requirements considered are those shown in Table 10 - Table 12. The life cycle diagram of the 'communal ASHP' system is shown in Figure 29; the schematic in Figure 30.

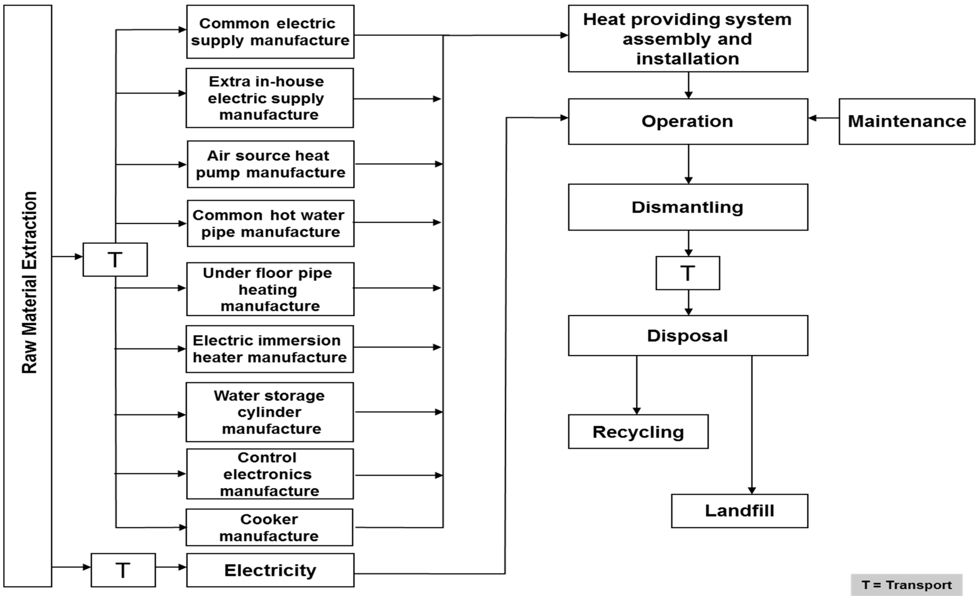


Figure 29 Life cycle flow diagram of the ASHP system used for heating and cooking.

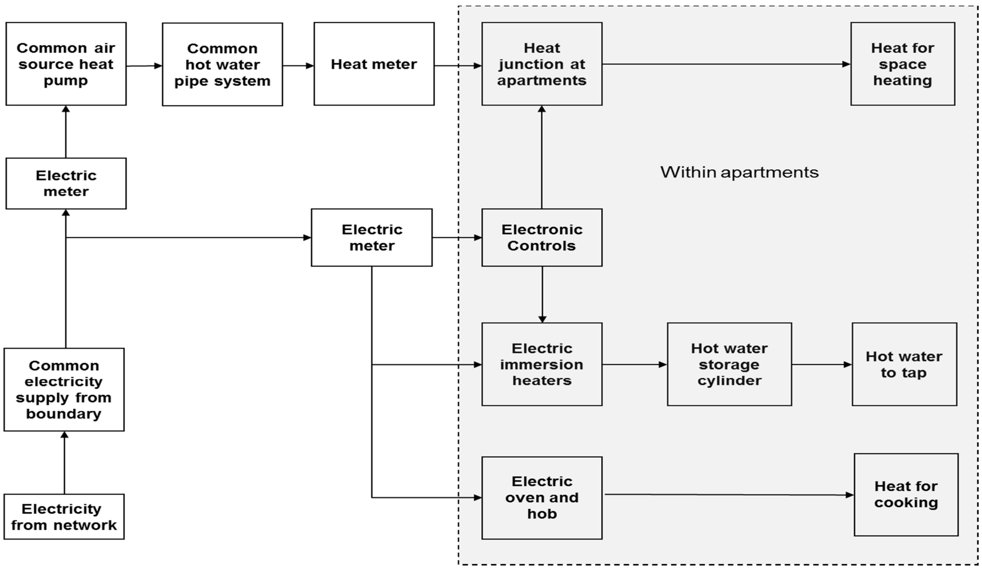


Figure 30 Schematic diagram of the ASHP heating and cooking system.

4.1.6.1 System description

Space heating: Space heating is provided for all apartments through a bank of nine *Dimplex* 28 kW ground level mounted electrically powered air source heat pumps. The bank of ASHP's is located in a small open compound close to the apartment block. Electricity is provided to the ASHP bank through underground cabling. Each ASHP is an air to water heat pump with two compressors and sound optimising to reduce noise. In addition, each unit has heat exchangers, fans, insulation and a refrigerant (R404A).

Manufacture is principally from steel, aluminium and copper. Maximum flow temperature is 55^{o}C and operational COP rated between 2.4 and 3.6. Hot water produced from the ASHP bank is pumped and distributed through a common plastic and then metal pipe system to each floor in the block and subsequently to a water distribution manifold within each individual apartment. The manifold and control valves evenly distribute the heated water to the relevant wet system that subsequently provides room space heating while a wall mounted programmer facilitates heat and time control for space and hot water heating. Electricity is also used of hot water circulation.

Water heating: Hot water for washing and showering is provided through the use of two 3,000 Watt electric immersion heaters electric immersion heaters installed within a highly insulated direct acting storage cylinder based on the same approach as described for the ‘electric panel and storage’ system.

Cooking: An electric hob and oven are used for cooking purposes.

Energy supply system: Grid electricity is supplied to the apartment block and individual apartments as described earlier for the electric panel and storage systems. An additional connection is made for the bank of ASHP’s requiring a three phase 415 volt supply. Householders arrange their own electricity suppliers for their hot water and cooking – this is generally standard rate and economy 7 or 10 so as to provide for cheaper overnight electricity especially for water heating. In addition, householders use a single contracted energy service company for their space heating energy provision.

Installation: As a new building - installation complexities have been minimised through the use of designed pipe and cable riser chambers and routes to each apartment. The outside bank of heat pumps requires a concrete base for installation whilst trenches are excavated and reinstated for the installation of hot water pipes to the apartment block.

Transportation: The heat pumps are transported from Northern Ireland (Dimplex, 2011) and water heating units from the manufacturing site in Norway. Both heat pumps and units are transported by ship and on the mainland by lorry to the installation site.

Maintenance: Maintenance of the space heating system to the individual apartments is the responsibility of the contracted energy service company whereas the other electricity services are covered by the relevant utility. There are no legal requirements for systematic electric heating maintenance, however it expected and recommended by the manufacturer that routine inspection and maintenance is conducted once per year for the community air source heat pumps.

Disposal: The air source heat pump would be removed from site and its component parts recycled. Prior to this the refrigerant would be removed from the system by trained and qualified workers using an established process of extraction and disposal. The hot water supply pipes would be removed and taken as scrap metal. The hot water storage cylinders are removed and recycled.

4.1.6.2 Impact assessment

Results from the LCA analysis are shown in Figure 31; in a similar manner to the electric panel system, the use of operational electricity by the community air source heat pump system has a sizable impact on the environment**.** The total GWP is equal to 8,831 tonnes over 40 years which is again mainly due to the electricity used – the GWP of only electricity is estimated at 8,657 tonnes over 40 years or 56.3 kg CO_2 eq./m^2 yr. This compares to Henderson and Young (2008) who found that using air source heat pumps produced 32.4 kg CO_2 eq./m^2 yr. from operational energy alone.

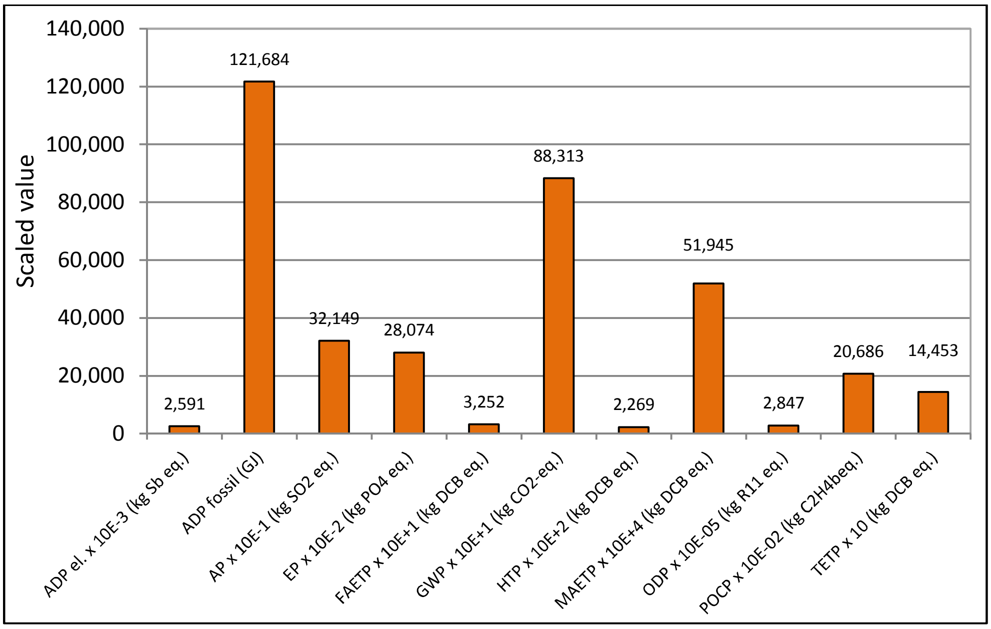


Figure 31 Life cycle environmental impacts for the ASHP system over a 40 year period.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

The contribution of different life cycle stages to each impact is shown in Figure 32**;** noting again that operational electricity dominates the impacts. From a life cycle perspective, the important impacts emerge from raw material extraction and manufacturing for all indicators, this spans from 1.5% to 53% of impacts with operational energy removed. Elsewhere, maintenance impacts are evident under ODP (4.5%) and HTP (3.5%) and connected with maintenance tasks on the common hot water system.

System components that contribute most to the impacts include: hot water storage cylinders, wet system and the heat pumps themselves - Figure 33. The use of stainless steel in the storage cylinder particularly impacts the TETP, HTP and FAETP indicators, offering contributions (62.0%, 41.8% and 41.1% respectively). The wet system using radiators and copper pipe provide important impacts for all indicators. The manufacture of the ASHP impacts particularly MAETP (22.0%) and GWP (16.6%). Overall the refrigerant offers comparatively small impacts at FAETP (0.5%) and EP (2%).

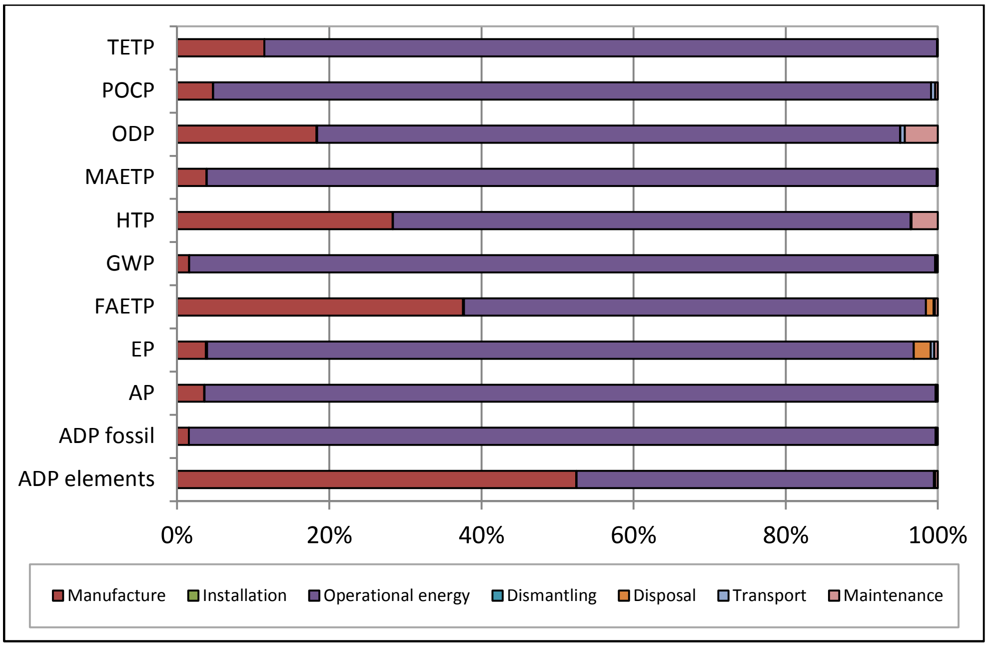


Figure 32 Contribution analyses for the ASHP system (including operational energy) over a 40 year period.

[Raw materials and manufacture are combined].

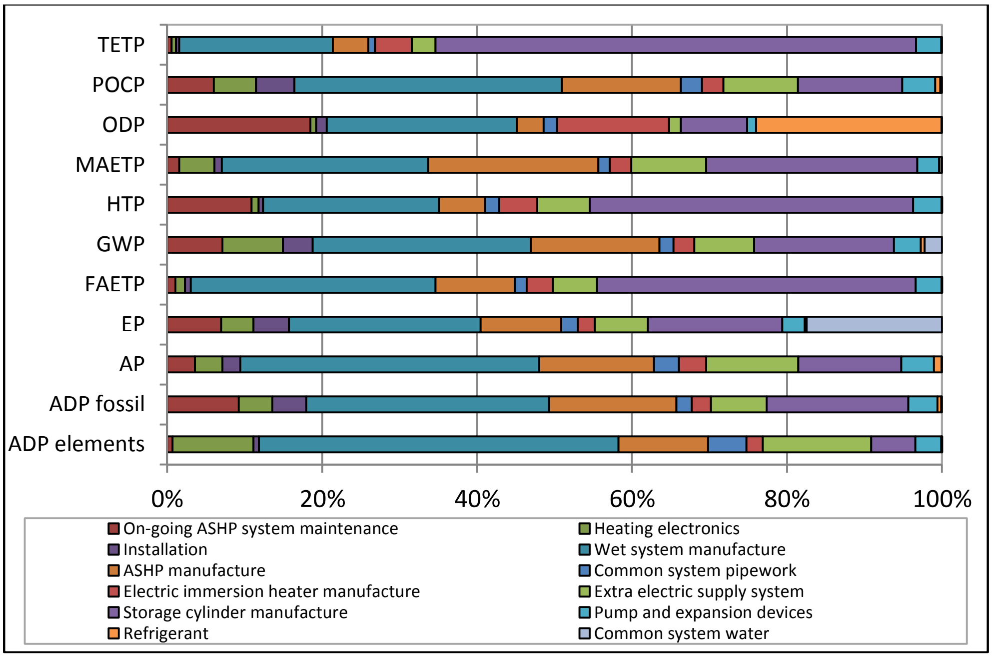


Figure 33 Contribution analysis for the ASHP system (operational energy removed) over a 40 year period.

4.1.7 Gas boiler system

The gas boiler system is installed in the *Roach Court* apartment block and provides for space and water heating along with household cooking needs. This system provides for hot water instantaneously and space heating gradually using individual apartment boilers. Specific energy requirements considered are those shown in Table 10 - Table 12; the life cycle diagram of the 'gas boiler' system is shown in Figure 34**,** and the schematic of the system in Figure 35**.**

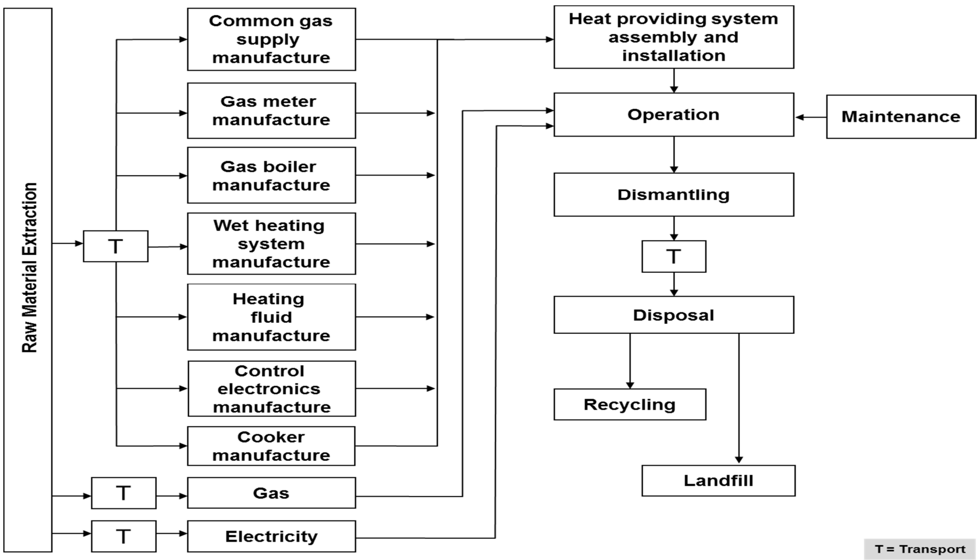


Figure 34 Life cycle flow diagram of the gas system for heating and cooking.

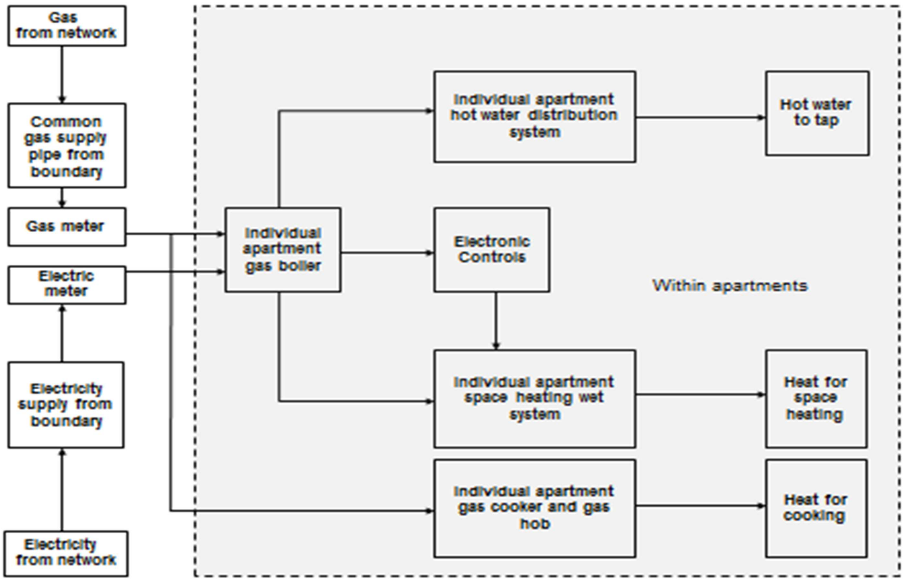


Figure 35 Schematic diagram of the gas system for heating and cooking.

4.1.7.1 System description

Space heating: Space heating is provided through a wall mounted and externally vented *24 kW Worcester Bosch Junior GreenStar 24i* combination natural gas boiler. The boiler is manufactured principally from steel, stainless steel and aluminium. The boiler heats water and circulates it to steel wall mounted radiators through a copper pipe wet system. The boiler and system is controlled by an electronic programmer and individual radiator thermostatic valves. The wet system contains a corrosion inhibitor fluid which is treated and disposed of periodically in a municipal wastewater treatment plant.

Water heating: Water heating is provided on-demand by the combination boiler directly to the apartment hot water pipe system.

Cooking: Cooking is conducted using gas hobs and gas ovens.

Energy supply system: Natural gas is distributed locally through gas distribution mains located close to the boundary of the apartment block. Generally a series of internal apartment block riser, service pipes and meter installations provide gas to each apartment. The gas enters service pipes at 30 mb pressure and an average calorific value range of 37.5 MJ/m^3 to 43.0 MJ/m^3 (Grid, 2011). Within the apartment, natural gas is supplied to the boiler and cooker through copper pipes from the gas meter installation. Significant building design and construction changes must be employed where natural gas is provided to such apartments. Riser pipes must be installed in well ventilated shafts according to the required standards (IGEM, 2006); these facilitate the natural and safe ventilation of the distribution pipes and meters. In addition to general household use, electricity is provided from the domestic system for the gas boiler power and the wet system water circulation pump. Households negotiate their own gas and electricity contracts with suppliers and these are metered separately for each apartment.

Installation: The gas boiler system requires extensive installation including, the fixing of brackets for the gas supply pipes, and entry through various floor levels requires drilling and refilling using concrete and expanding foam. The gas boiler and radiators need securing to the walls and the boiler external flue pipe installed.

Transportation: The gas boiler is transported from Worcestershire by lorry to the installation site.

Maintenance: An annual maintenance inspection and service is required for the gas boiler. Further, five yearly maintenance checks are conducted on the external space heating system. Such maintenance activities within apartments are organised and paid for by apartment owners, landlords, or housing agency where rented, whereas common supply systems such as gas, electricity and water are covered by the relevant utilities.

Disposal: Gas boilers are removed from apartments and processed for material recycling - copper pipework and radiators are easily recyclable.

4.1.7.2 Impact assessment

Results from the LCA analysis are shown in Figure 36 and show the gas system impacts on the environment through its use of operational gas and a smaller amount of electricity. For example, the total GWP is equal to 4,306 tonnes over 40 years which is mainly due to the gas and electricity used – the GWP impact for gas use over 40 years is estimated at 4,113 tonnes or 26.8 kg CO_2 eq./m^2 yr and that for electricity use at 72 tonnes or 0.5 kg CO_2 eq./m^2 yr. This compares to Henderson and Young (2008) who found that individual gas boilers used for both space and water heating produced CO_2 emissions of 24.28 kg CO_2 eq./m^2 yr.

Natural gas burning in individual boilers and its associated electricity usage for powering the system is important, particularly within the ADP - fossil and GWP indicators (97.0% and 96.9% respectively). Contributions to the EP indicator at 82.3% appear through the use of natural gas and the associated emissions to sea water during the production of natural gas.

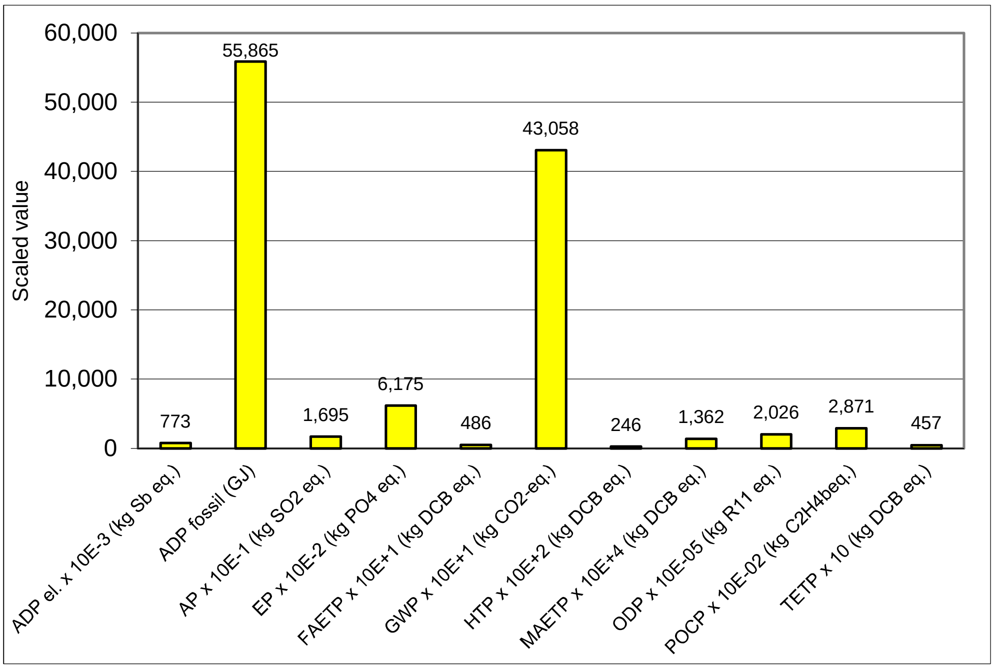


Figure 36 Life cycle environmental impacts for the gas system over a 40 year period.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

The contribution of different life cycle stages to each impact is shown in Figure 37 - operational energy dominates the impacts spanning from only 3% (ADP elements) to 97% (ADP fossil and GWP). Other contributors include: raw materials and manufacture with ADP elements (93%) and FAETP, HTP, TETP at 63%.

The contribution of other parts of the life cycle when operational gas and electricity is removed from the results is shown in Figure 38. Key impacts are derived from: the space heating wet system, individual gas boilers and the on-going system maintenance.

The substantial use of copper and steel for piping and radiators within the wet system contributes to impacts in all indicators ranging from 23% to 65.8%. The gas boilers used provide contribution impacts particularly in the ADP fossil at 591 GJ and 37.3%, GWP at 4.32 t CO_2 and 35.6% and MAETP at 25,280 t DCB, and 33.3% indicators; this is through the extensive use of steel in boilers and the powder coating for the boiler covers. On-going maintenance for the gas system provides impacts principally in the

ODP indicator at 61.9% contribution, especially halogenated organic emissions to atmosphere through the use of PTFE sealing tape for pipe fittings.

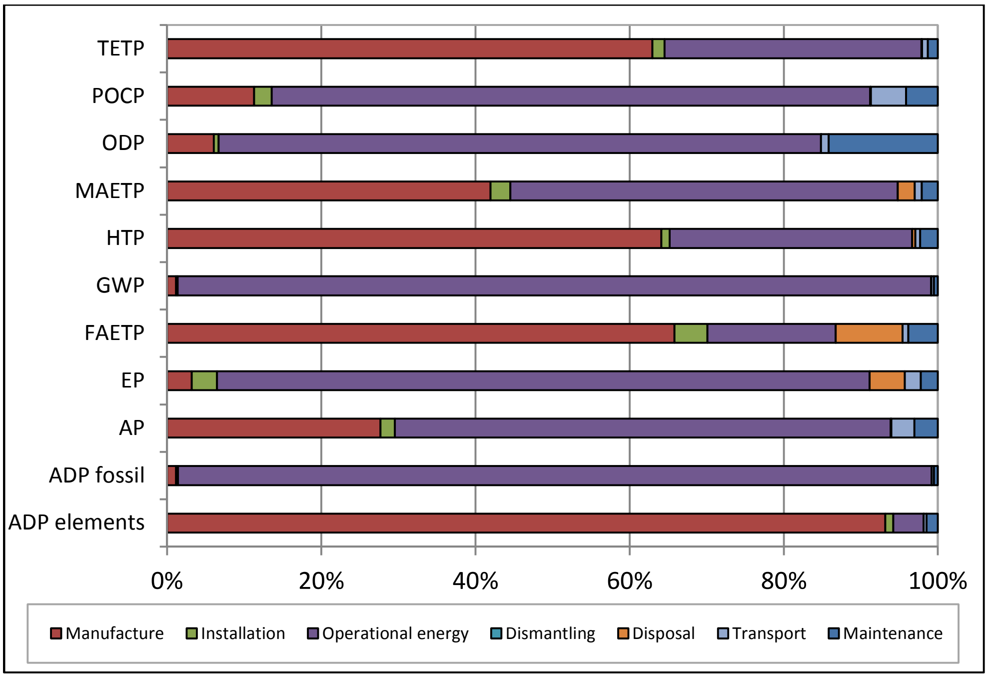


Figure 37 Contribution analysis for the gas system (incl. operational energy) over a 40 year period.

[Raw materials and manufacture are combined].

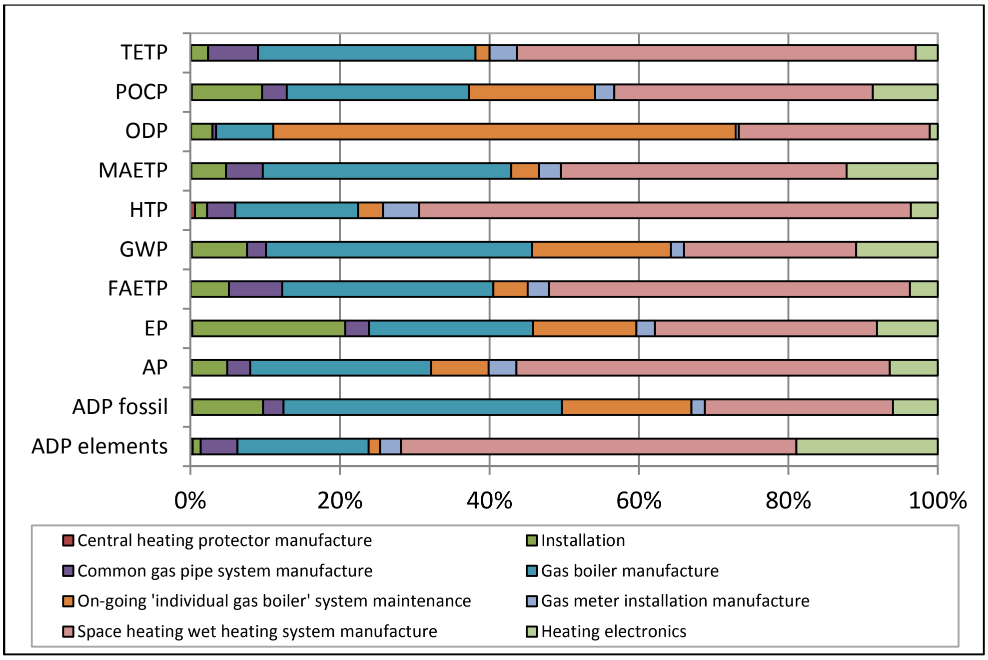


Figure 38 Contribution analysis for the gas system (operational energy removed) over a 40 year period.

4.1.8 Combined gas and electric system

The combined gas hot water and electric space heating system as installed in the *Christabel and Sylvia* apartment blocks. The combined gas hot water and electric space heating system uses centralised natural gas heaters for common hot water provision and electric resistance panel heaters for apartment space heating. Electricity is also used for hot water pumping and cooking. This can therefore be deemed as a 'hybrid' heating system. Specific energy requirements considered are those shown in Table 10 - Table 12 and the life cycle and schematic of the 'combined gas and electric system' is shown in Figure 39 and Figure 40 respectively.

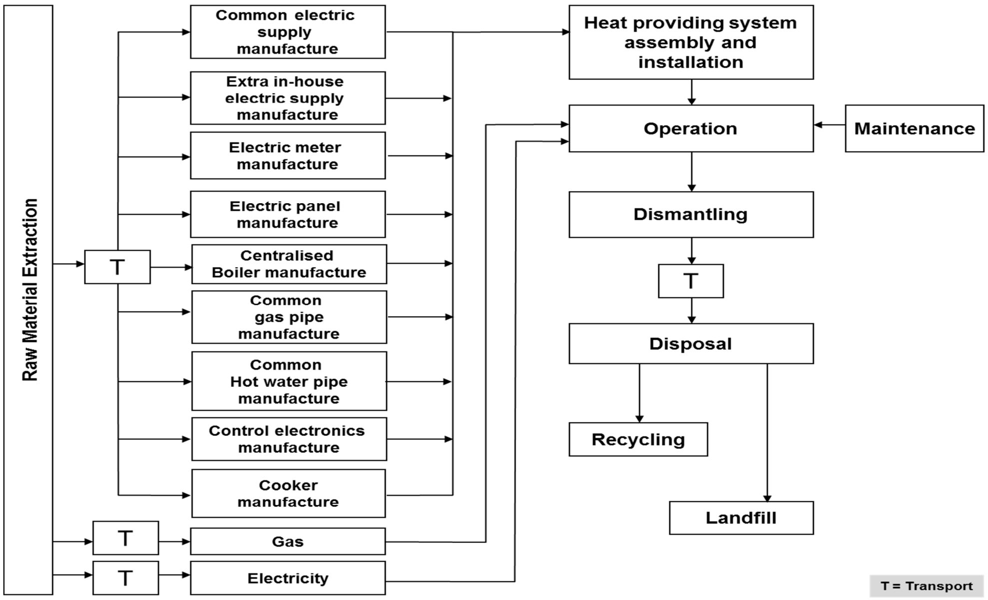


Figure 39 Life cycle diagram of a combined system for heating and cooking.

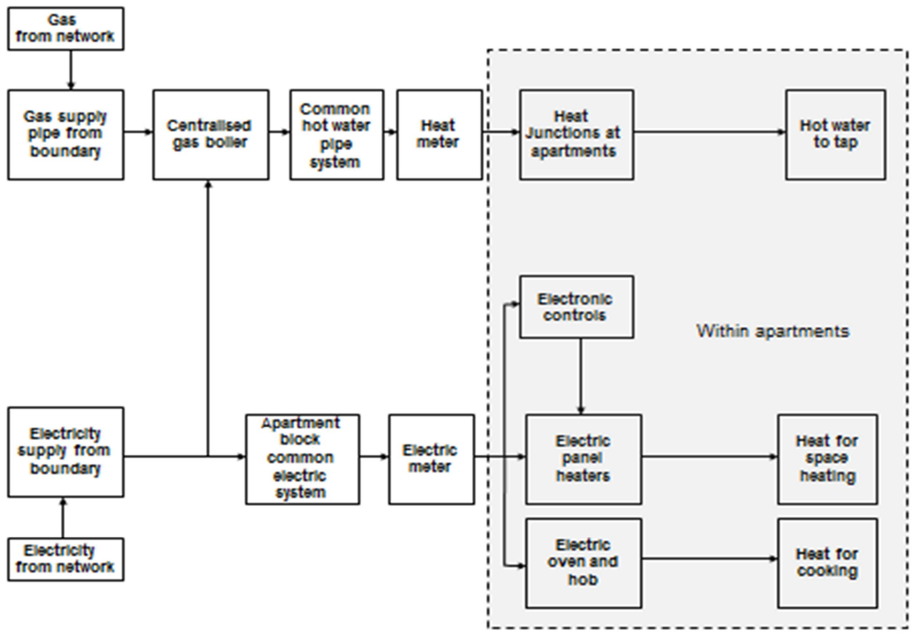


Figure 40 Schematic diagram of a combined system for heating and cooking.

4.1.8.1 System description

Space heating: The combined system uses the same panel heaters as described earlier for the electric panel system. A steel oil filled electric heated towel rail is provided in the bathroom.

Water heating: Two *Andrews* 78 kWh roof mounted gas fuelled water heater and storage boilers provide hot water to a common supply network. The gas heaters are made from a stainless steel welded tank and steel outer casing with insulation installed in-between. The two boilers, circulation pumps and valves are managed by an electrical controller located in the boiler house. The boilers are vented to the outside using a steel flue and fan arrangement. Centralised hot water is supplied on-demand from the storage tank to individual apartments through an insulated steel and copper pipe network within service ducts. This metered hot water is available for culinary and washing purposes only.

Cooking: In this system there is no direct provision of gas to apartments therefore cooking is by electric oven and hob.

Energy supply system: A 75mm diameter welded steel wall mounted pipe provides low pressure natural gas from the local grid to the roof mounted boilers via the external wall of the block and under the ventilated panelling. Electricity is supplied in the same manner as for the electric panel system. Households are presently obliged to use a single contracted energy service company to provide hot water, cold water and electricity – this is periodically negotiated with the residents association. There is no provision within the apartment block for off-peak electricity to be supplied or metered although standard rate electricity and hot and cold water are individually metered close to or at the entry point to each apartment.

Installation: The gas supply pipe to the roof boilers is attached to the apartment block external wall using brackets and stabilisers. The boilers are installed on a concrete base and holes made for the external flue pipes. Hot water pipes to apartments are fixed within vertical service chambers.

Transportation: Each gas boiler was transported from Birmingham by lorry to the installation site while the electric panels are transported to Manchester from Northern Ireland using ferry and lorry.

Maintenance: Annual checks and servicing are conducted on the two gas boilers. The electric space heating system is checked every five years. Maintenance of the hot water supply system and boilers is the prerogative of the energy supply company whereas other common supply services such as electricity and cold water are covered by the relevant utility.

Disposal: The electrical parts of the system follow the disposal process as described for the electric panel system. The common hot water pipes are removed from the apartment block and transported for recycling especially the copper and steel components. The two gas boilers are also removed for recycling.

4.1.8.2 Impact assessment

Results from the LCA analysis (see Figure 41) show that the combined system has an impact on the environment through its high use of operational electricity for space heating and to a lesser extent natural gas for individual apartment hot water. For example, the total GWP is equal to 8,562 tonnes over 40 years which is mainly due to the electricity and gas used - the GWP impact for electricity use over 40 years is estimated at 6,528 tonnes or 42.5 kg CO_2 eq./m^2 yr. for electric heating and for gas use at 1,925 tonnes or 12.5 kg CO_2 eq./m^2 yr. This compares to Henderson and Young

(2008) who found that gas community heating for both space and hot water heating produced CO_2 of 26.79 kg CO_2 eq./m^2 yr.

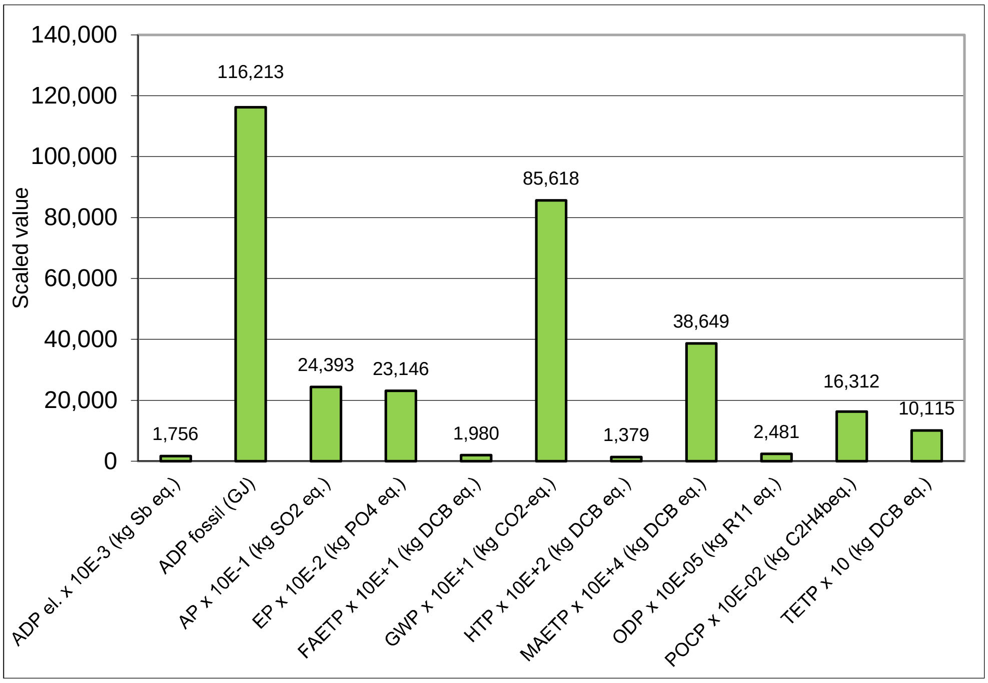


Figure 41 Life cycle environmental impacts for the combined system over a 40 year period.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

The contribution of different life cycle stages to each impact is shown in Figure 42. Operational energy forms 52% - 99% of all impacts. In addition, ADP elements (46%) and FAETP (21%) represent the highest contributors within the manufacturing category and particularly from the electric panel heaters, centralised boilers and the common block electric system – see Figure 43. Electric heating panel’s exhibit impacts to the ADP fossil, FAETP, and AP indicators, (36.1%, 35.3%, and 34.0% respectively). This is attributable to the steel used in manufacturing and the impacts of the steel product manufacturing required. Impacts from the centralised boiler include; TETP 48.0% and HTP 36.4% indicators – these are mainly from the stainless steel used in the storage tank of the boiler. Other contribution categories provide relatively small impacts overall.

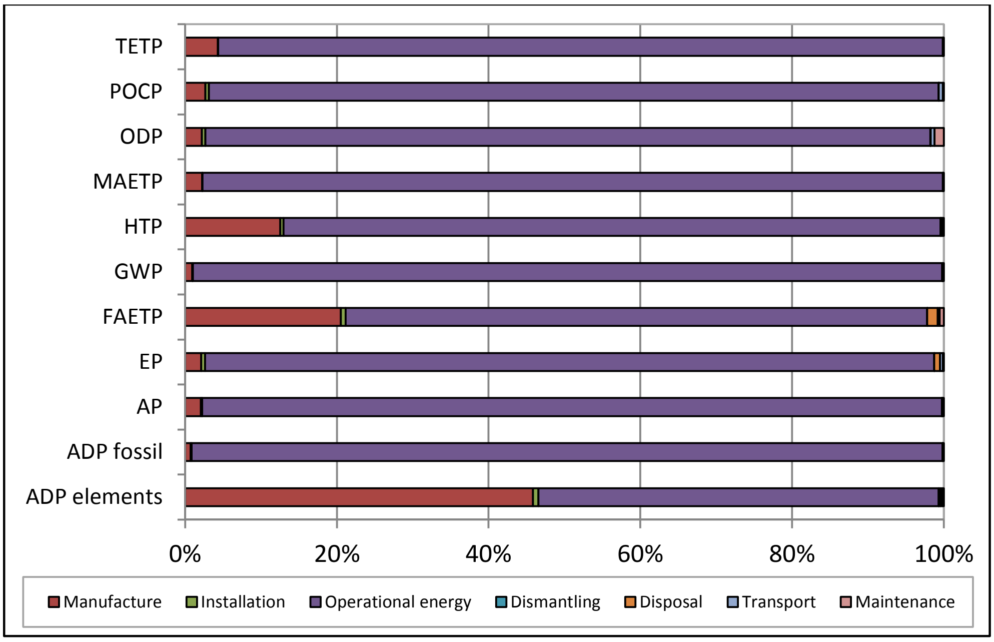


Figure 42 Contribution analysis for the combined system (incl. operational energy) over a 40 year period.

[Raw materials and manufacture are combined].

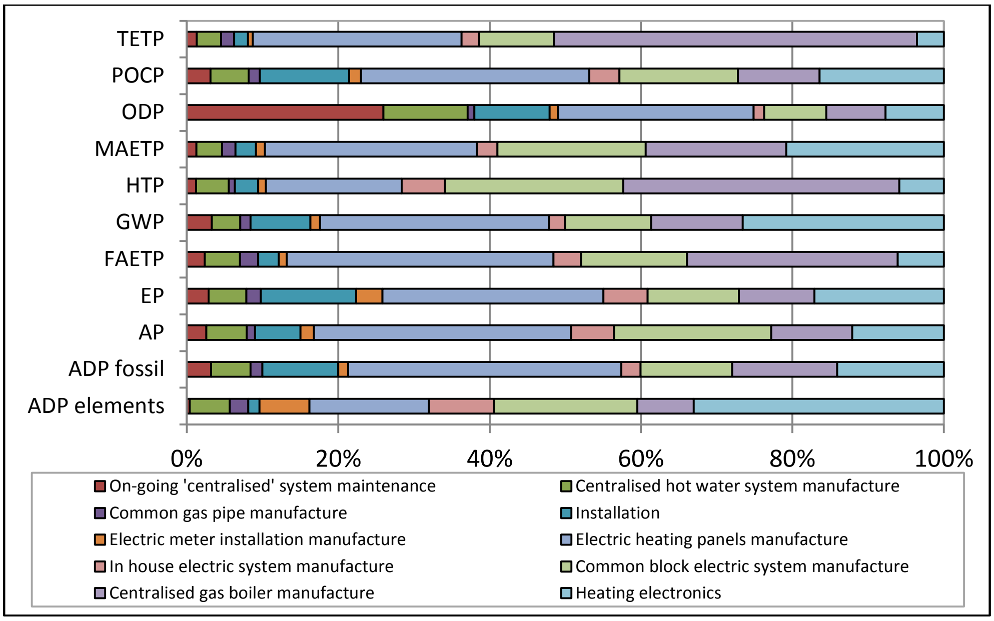


Figure 43 Contribution analysis for the combined system (operational energy removed) over a 40 year period.

4.1.9 District heating system

The district heating system is hypothetically installed in the *Coley* apartment block and provides for both space heating and domestic hot water needs. The district heating system uses natural gas as its fuel source and serves three apartment blocks from an energy centre through a substantial hot water distribution system. This system provides for stored hot water and gradual space heating. Specific energy requirements considered are those shown previously in Table 10 - Table 12, the life cycle diagram of the 'district heating system' is shown in Figure 44 and the system schematic in Figure 45.

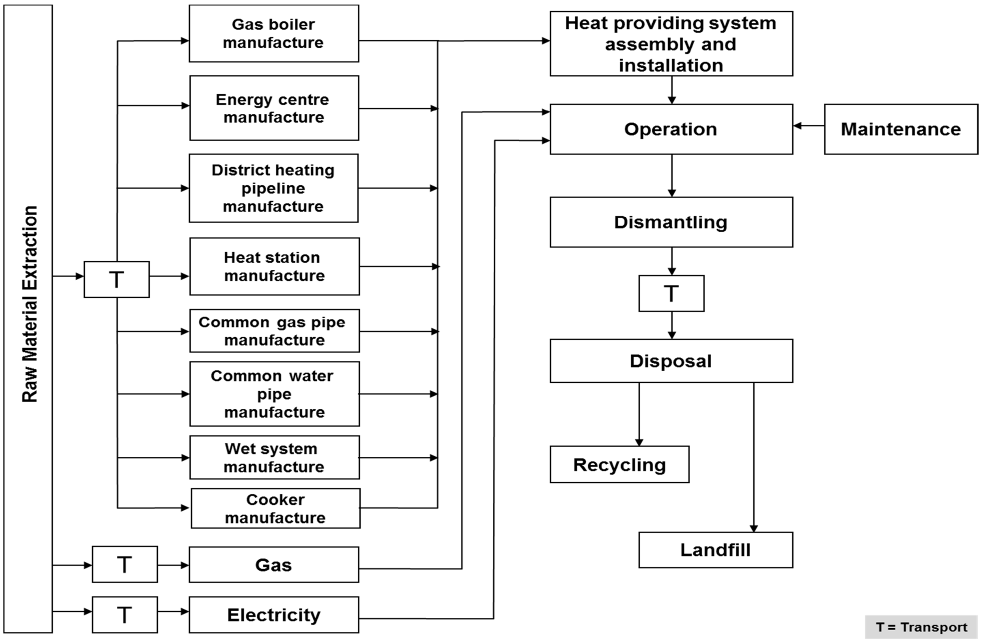


Figure 44 Life cycle flow diagram of the district heating system used for heating and cooking.

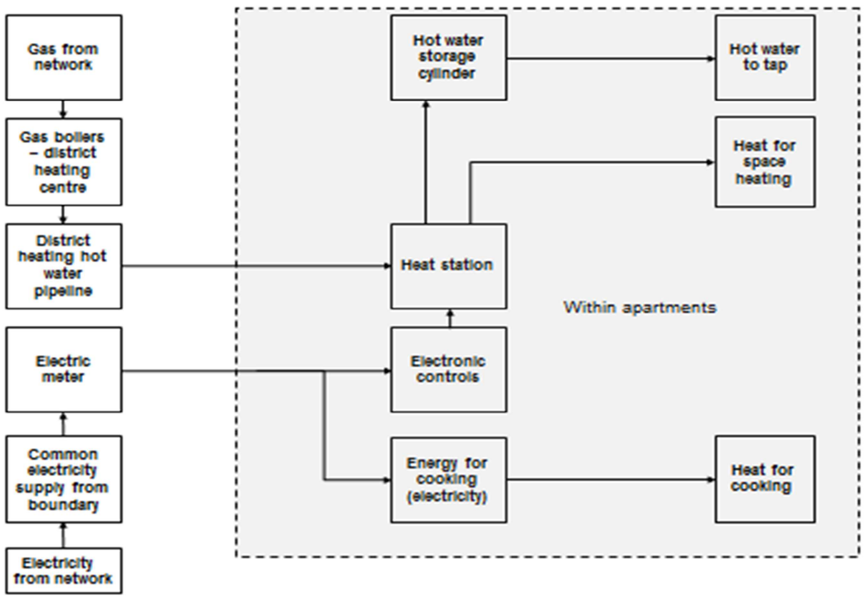


Figure 45 Schematic diagram of the district heating and cooking system.

4.1.9.1 System description

Space heating: Space heating for each apartment is conducted as described earlier for the gas system using a wet system. However, the heated water is taken from a heat station[6] installed within the flat and fed with hot water from the district heating system.

Water heating: In a similar manner to space heating, domestic hot water for washing, showering and culinary purposes is also provided from the heat station to a hot water storage cylinder for final use on a demand and reheat basis.

Cooking: Electricity is used for cooking through the use of electric hobs and ovens. In addition, it is also used for water pumping, heating control, lighting and appliances.

Energy supply system: A small energy centre is located in a specifically provided building close to the apartment blocks and supplies thermal heat for household use. For each apartment block, three installed *Potterton WH110* gas condensing boilers, each rated at (110 kW) are heated using natural gas fed by pipe from the local distribution system. Thermal heat from the boilers is retained in a thermal store ready for distribution to each apartment block through a series of pumps and a highly insulated polyethylene pipe network buried in trenches. At the apartment block, a pump set and heat exchanger circulate hot water to insulated steel riser and feeder pipes that take the hot water to individual apartments. At the apartments, heat stations using heat exchangers and electronics regulate, meter and pump the water according to temperature and household demand requirements.

Householders negotiate their own electricity contracts but also use and pay for their heat supply through an energy supply company that manages and controls the district heating system and supply.

Installation: Installation is a large and complex activity for the district heating system requiring the construction of new buildings, trench excavation, the laying and jointing of pipes and final reinstatement to bring heat to each apartment block. Within the blocks a similar installation approach is required as described earlier for the 'combined and gas systems' but with heat stations wall mounted.

[6] Heat stations are also known as hydraulic interface units

Transportation: The main gas boilers and heat stations are transported from Germany, and the plastic distribution piping from Chesterfield – UK.

Maintenance: The equipment within the energy centred is serviced on an annual basis with maintenance activities as and when required. Leakage of both water and heat from the distribution system is monitored and repairs conducted as soon as these are detected.

Disposal: The extensive district heating system contains a high quantity of metals that can be recycled – apartment block hot water pipes and heat stations. The underground water pipes would not be removed or recycled. The energy centre and the gas boilers would be removed for scrap processing.

4.1.9.2 Impact assessment

Results from the LCA analysis are shown in Figure 46; in a similar manner to the gas boiler system, the use of operational gas by district heating boilers has a sizable impact on the environment. For example, the total GWP is equal to 4,597 tonnes over 40 years which is mainly due to the gas used – the GWP impact for gas use over 40 years is estimated at 3,531 tonnes or 22.9 kg CO_2 eq./m^2 yr. Electricity GWP is 926 tonnes over 40 years or 6.02 kg CO_2 eq./m^2 yr. This compares to Henderson and Young (2008) who found that centralised boilers for district heating produced CO_2 emissions of 27.56 kg CO_2 eq./m^2 yr. Natural gas burning in the district heating boilers is important particularly within the ADP - fossil and GWP indicators forming 75.6% and 76.8% respectively.

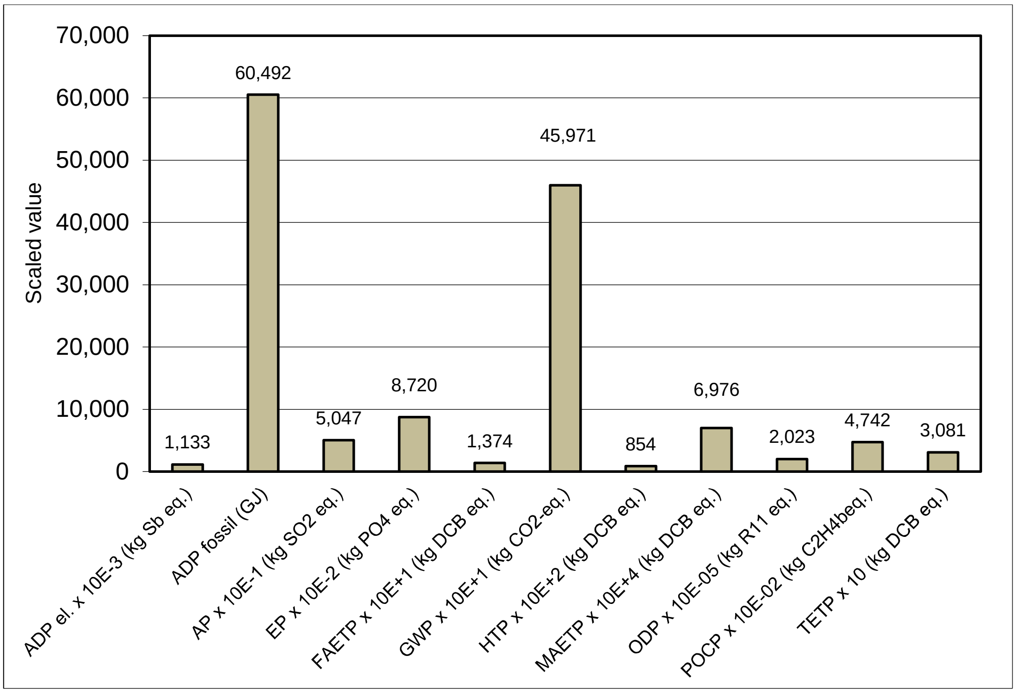


Figure 46 Life cycle environmental impacts for the district heating system over a 40 year period.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

Operational gas dominates the impacts with overall contribution values from 13% to 97% for all categories - Figure 47. The next largest contributor is raw materials and manufacturing with ADP elements (80%) and FAETP (73%), impacts coming from space heating wet system and hot water storage cylinders.

The contribution of other parts of the life cycle when operational gas and electricity is removed from the results is shown in Figure 48**.** When considering only system components, key impacts are derived from: the wet systems, cylinders and centralised boiler manufacture. The wet systems exhibit the same impacts described for the gas boilers system previously and the cylinders as per the electric panel and storage systems. The centralised boilers provide contribution impacts particularly in the TETP (22%), MAETP (20.5%) and FAETP (19.6%), this is through the extensive use of steel in boilers and the powder coating for the boiler covers. The substantial use of copper and steel in each heat station provides impacts HTP (12.8%), and TETP (12.5%).

Elsewhere, the installation of the main distribution pipes provides important impacts to the ADP fossil (8.6%) and POCP (7.9%) indicators. The processing required during manufacture has impacts in the AD fossil 19.9% and GWP 21.9% indicators mainly through the energy required within each process stage especially sheet metal forming and copper pipe extrusion. Under the waste management indicator, the EP indicator is highlighted at 22.8% - this reflects the periodic disposal of the distribution network water.

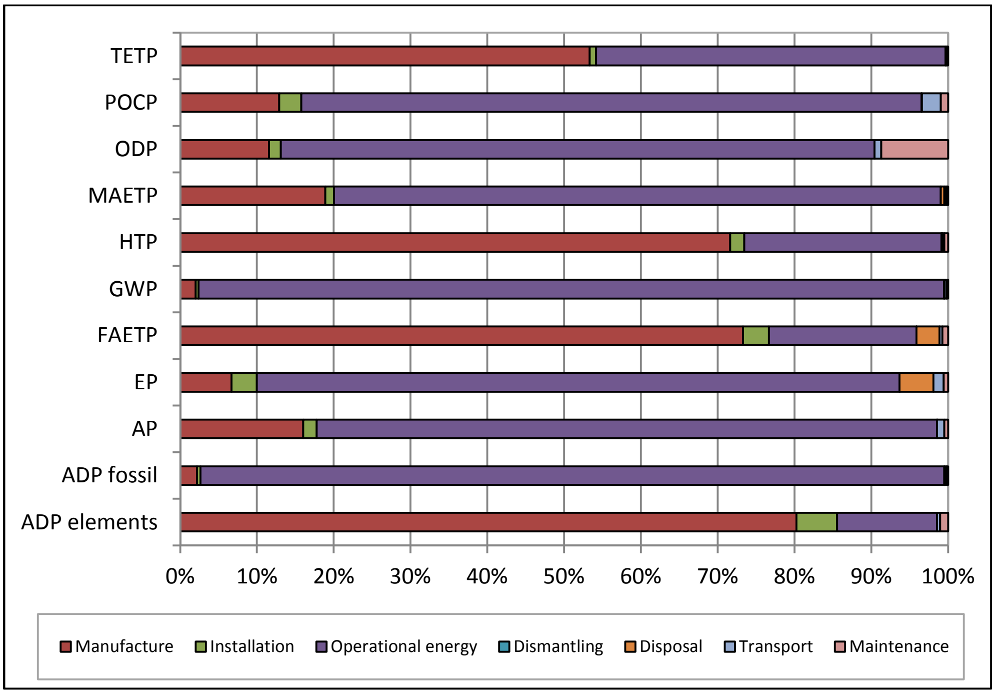


Figure 47 Contribution analyses for the district heating system (incl. operational energy) over a 40 year period.

[Raw materials and manufacture are combined].

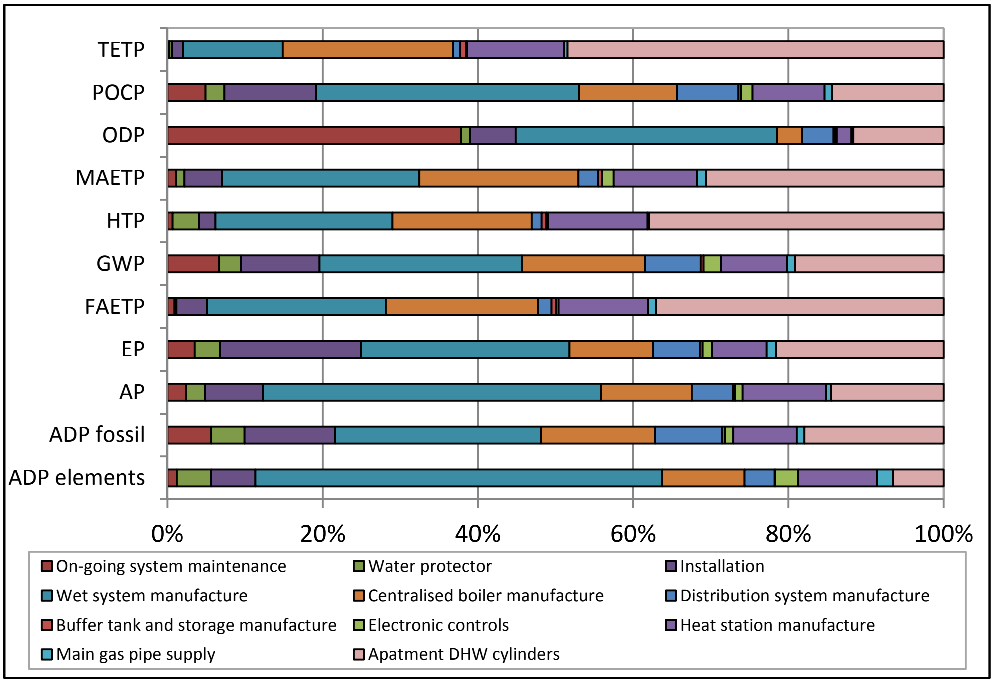


Figure 48 Contribution analysis for the district heating system (operational energy removed) over a 40 year period.

4.1.10 Combined heating and power system

The community combined heating and power system (CHP) is installed in the *CHIPs* apartment block and provides for space and water heating along with the provision of generated electricity to the apartment block through the private electric network and in addition, as feed-in to the national electricity grid system. Specific requirements considered are those shown in Table 10 - Table 12 previously, the life cycle diagram of the 'community combined heating and power' system is shown in Figure 49 and the system schematic shown in Figure 50.

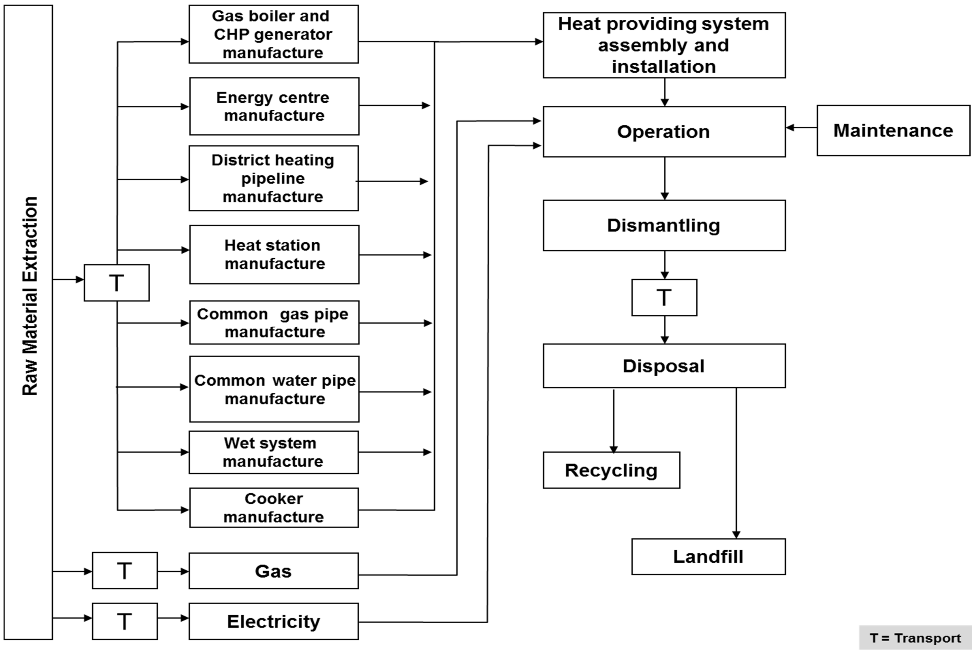


Figure 49 Life cycle flow diagram of the community combined heating and power system used for heating and cooking.

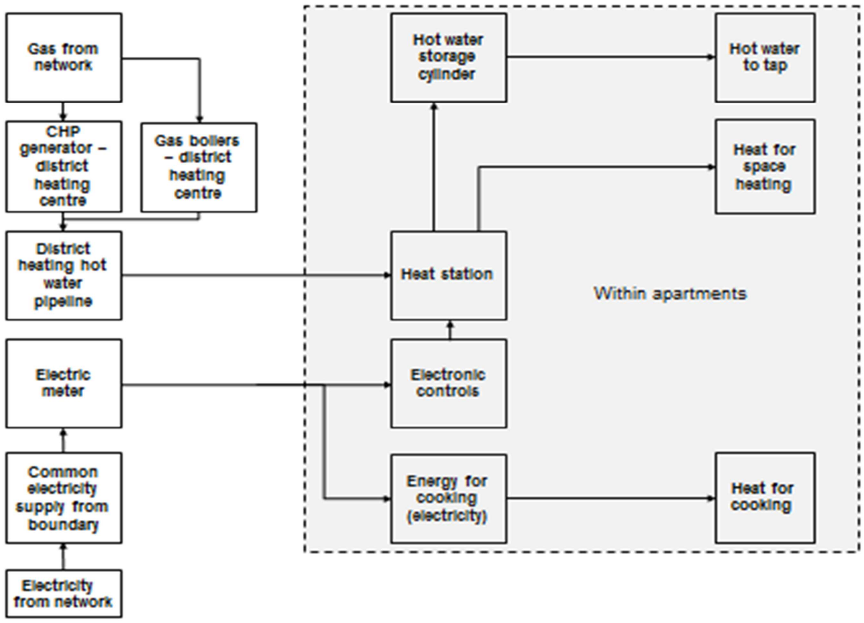


Figure 50 Schematic diagram of the community combined heating and power and cooking system.

4.1.10.1 System description

Space heating: Apartment space heating operates as per the district heating system via the apartment heat station.

Water heating: Apartment water heating operates as per the district heating system via the apartment heat station.

Cooking: Electricity is used for cooking through the use of electric hobs and ovens. In addition it is used for lighting, appliances, water pumping and heating control.

Energy supply system: The energy supply and distribution system corresponding to that described earlier for the district heating system. However, also within the energy centre building, a combined heat and power unit is installed alongside to that of the gas condensing boilers and overall system design allows for energy continuity. Natural gas fed from the local gas distribution system is used to generate thermal heat but in the case of the CHP unit also electricity. The provision of heat is the lead for the CHP unit with electricity generation as secondary. The CHP has a rating of 50 kWe and 81 kWth – a typical unit being a *Viessman EM-50/81 CHP unit Vitobloc 200.* The CHP unit is a four cylinder four stroke engine and the electricity alternator produces 400 Volts at 50 Hz. Heat from the boilers and CHP unit is distributed to the apartment block and apartments following the same approach as for the district heating system. The CHP unit is there essentially to provide base load heat demand which in this case would be predominately hot water service. Operating hours should be a minimum of 4,000 to 5,000 hours per year at full load with the remainder and any peak supplied through the gas boilers. The boilers follow a cascading approach and are modulating.

Installation: Installation of the system follows that of the district heating system. Further work is required to provide power cables, switching and metering equipment for the electricity generation side of the CHP unit.

Transportation: The CHP unit, the supporting gas boilers and apartment heat stations are all transported from Germany while the plastic distribution piping from Chesterfield.

Maintenance: In addition to the requirements stated earlier for the district heating systems – the CHP unit requires good management of the plant operation and maintenance (DECC, 2013a) noting the requirement for prime mover maintenance and site maintenance. Given correct maintenance and operation, a gas engine should achieve an average availability of around 88% to 92% (DECC, 2013a). Service overhauls could typically be required every 5,000 hours of running and more major maintenance every 10,000 to 20,000 running hours (DECC, 2013a).

Disposal: The CHP system would follow the same disposal process as described for the district heat system. The CHP unit and hot water cylinder would be removed and transported for metal recycling.

4.1.10.2 Impact assessment

Results from the LCA analysis are shown in Figure 51; in a similar manner to the district heating system, the use of operational gas by CHP unit and the district heating boilers has a sizable impact on the environment. For example, the total GWP is equal to 4,491 tonnes over 40 years which is mainly due to the gas used – the GWP impact for gas use over 40 years is estimated at 3,146 tonnes or 20.5 kg CO_2 eq./m^2 yr. The use of electricity within the system, when considered directly provides a GWP impact of 926 tonnes over 40 years or 6.03 kg CO_2 eq./m^2 yr. This compares to Henderson and Young (2008) who found that a CHP fed district heating produced CO_2 emissions of 23.42 CO_2 eq./m^2 yr.

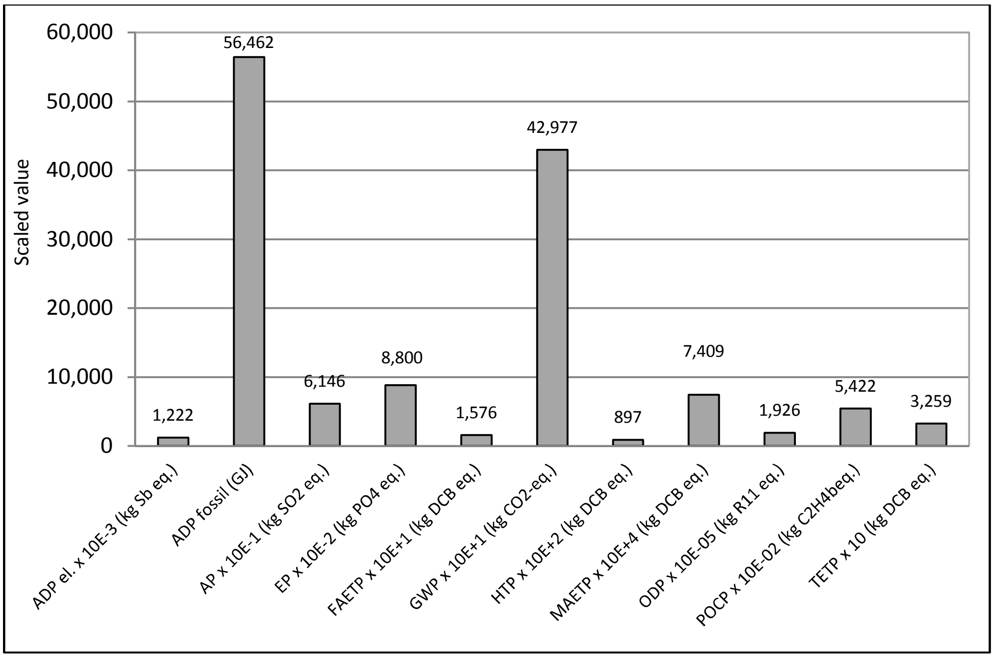


Figure 51 Life cycle environmental impacts for the community combined heating and power over a 40 year period.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

The contribution of different life cycle stages to each impact is shown in Figure 52. The use of operational gas over the 40 years dominates the impacts - natural gas burning in the CHP unit and boilers is vital particularly within the GWP and ADP fossil indicators at 91.7% and 91.2% respectively. Further environmental burdens are avoided with this system through the generation of a moderate level of electricity by the CHP unit reducing the power required from the national grid. Elsewhere, in addition to the operational energy supplied, the raw materials and manufacture were mainly responsible for these contributions – this is seen within the ADP elements (84%) and FAETP (81%) and comes especially from the CHP unit and apartment space heating wet systems.

Figure 53 shows the contribution of other parts of the life cycle when operational gas and electricity is removed from the results. When considering only system components, key impacts are derived from: the cogeneration components, wet systems, and apartment hot water cylinders. The cogeneration components provide large contribution impacts in all indicators ranging from 75.9% to 23.4% of impacts. The substantial use of copper and steel for piping and radiators within the wet system contributes to impacts in all indicators ranging from 39.9% to 8.97%. Elsewhere the hot water cylinders particularly impact the TETP 35.5% and HTP 28.9% indicators.

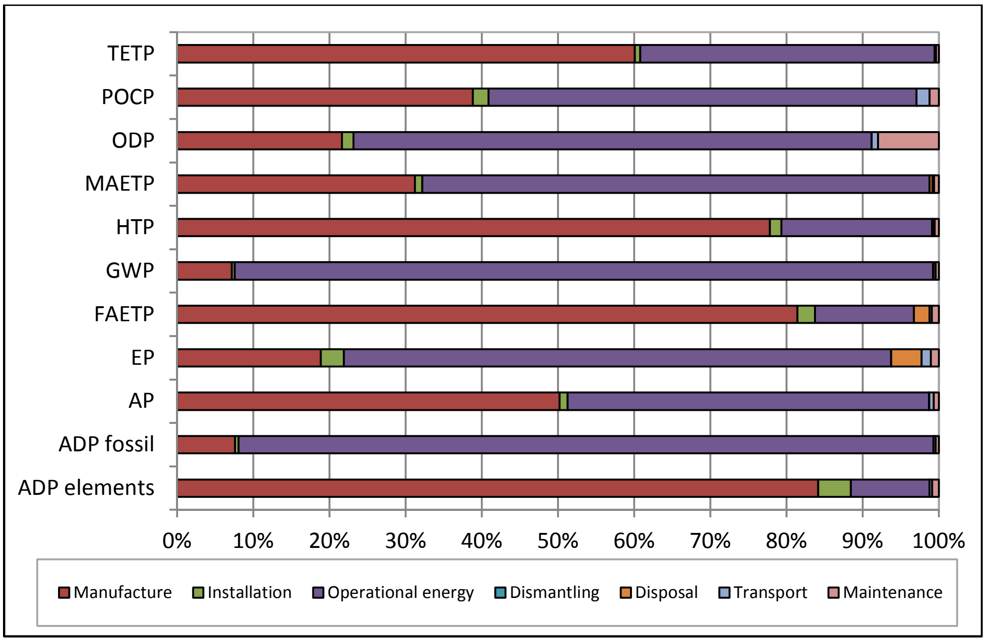


Figure 52 Contribution analyses for the community combined heating and power system (incl. operational energy) over a 40 year period.

[Raw materials and manufacture are combined].

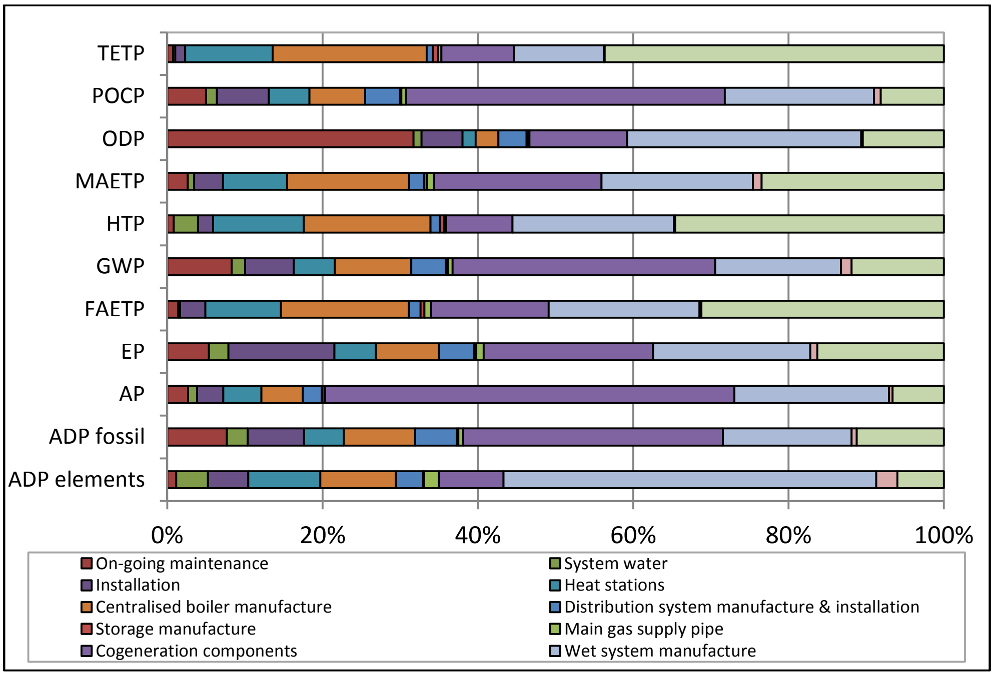


Figure 53 Contribution analysis for the community combined heating and power system (with operational energy removed) over a 40 year period.

4.1.11 Combined solar thermal and gas system

The solar thermal and gas system is installed in the *Northpoint* apartment block located in Islington, London. The system consumes gas from the local distribution network and heat energy from a roof top mounted solar thermal array. Natural gas is used for space heating, cooking and a proportion of the water heating. Solar thermal heat is utilised for the remainder of the water heating requirements. Specific energy requirements considered are those shown in Table 10 - Table 12. The life cycle diagram of the 'solar thermal and gas' system is shown in Figure 54 and the schematic in Figure 55.

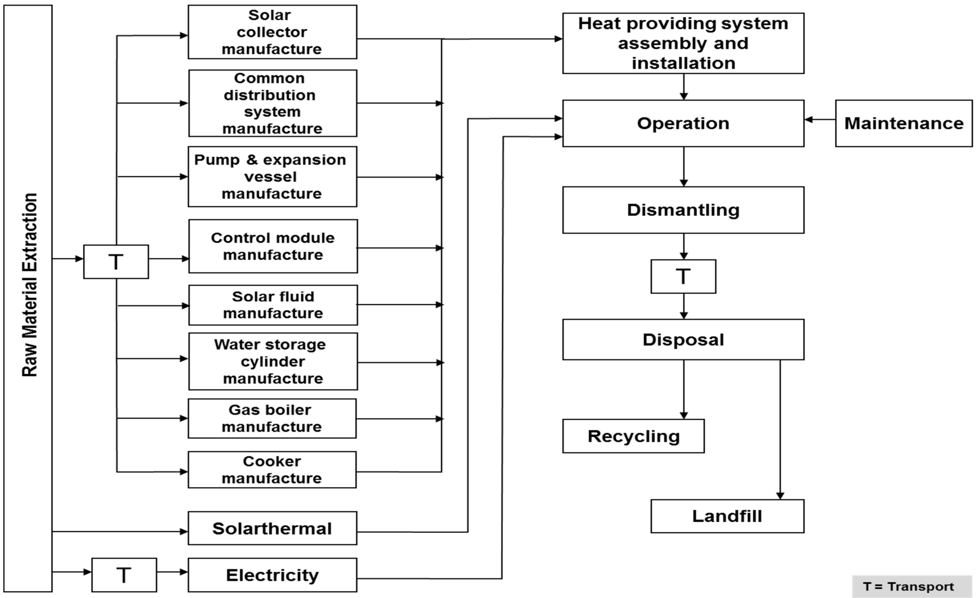


Figure 54 Life cycle flow diagram of the combined solar thermal and gas system used for heating and cooking.

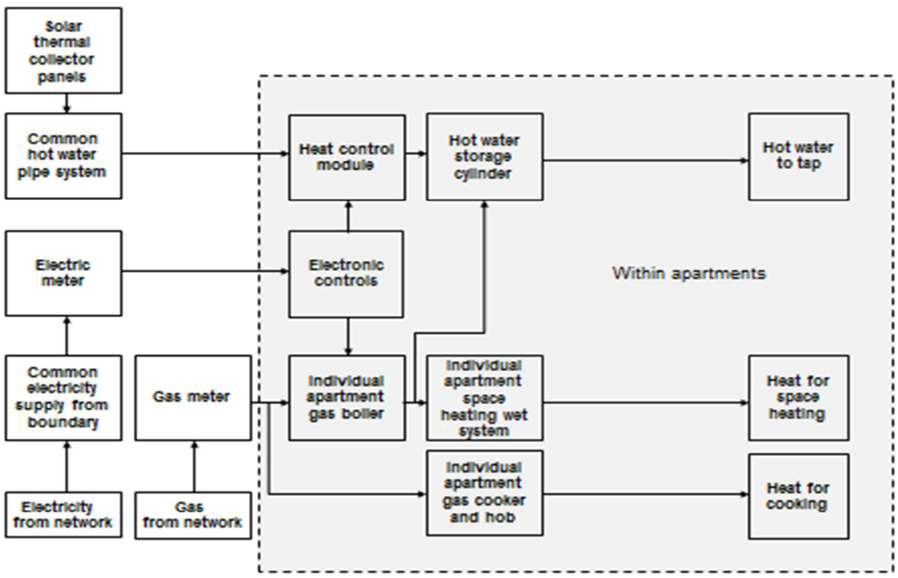


Figure 55 Schematic diagram of the combined solar thermal and gas system and cooking system.

4.1.11.1 System description

Space heating: A boiler provides space heating to the apartment through an installed wet system as previously described for the 'gas boiler system'. The boiler is an externally vented and wall mounted *12 kW Potterton 12SL condensing* natural gas boiler.

Water heating: A roof mounted solar thermal array is constructed using 50 individually linked *Viridian clearline* panels of 3 m^2 each and providing heated water to a common fed system supplying each floor and individual apartments. A wall mounted heat control module in each apartment regulates the solar thermal heat to an insulated indirect hot water storage cylinder based on existing storage temperature and solar hot water temperature. The cylinder hot water can also be supplementary heated through the use of the condensing gas boiler described under space heating.

Cooking: Cooking is conducted using gas hobs and gas ovens.

Energy supply system: Gas is supplied from the distribution system through individual gas service pipes mounted on the external face of the building. Electricity is supplied for common solar water pumping and control, apartment boiler operation and lighting and appliances. Solar thermal heat is supplied through the common pipe network and provided to each apartment on a balanced and equitable basis.

Householders negotiate their own gas and electricity contracts with relevant suppliers. Supplies are individually metered while the heat energy from the solar thermal system is metered and paid by householders to an apartment block energy association.

Installation: The solar thermal and gas system requires extensive installation including the assembly and fixing of the solar array on the building roof, the fixing of riser and feeder water pipes within service ducts, the fixing of control modules and gas boilers and the mounting and piping of radiators and flues of gas boilers for each apartment.

Transportation: The solar panels and individual control modules are transported from Cambridge, hot water cylinders from Norway and the gas boiler from Germany.

Maintenance: Maintenance for the gas aspects follows that of the gas boiler system described earlier. The solar thermal system requires monthly inspection and annual maintenance to keep it reliable and efficient. Regular inspection includes cleaning of the thermal arrays, testing of pumps and location and curing of any water leakage.

Disposal: The gas aspects of this system would follow the disposal approach as described for the individual gas boiler system. The solar thermal panel has high aluminium content and would normally be processed for recycling.

4.1.11.2 Impact assessment

Results from the LCA analysis are shown in Figure 56 and show the solar thermal and gas system impacts on the environment through its use of operational gas and a smaller amount of electricity. For example, the total GWP is equal to 4,131 tonnes over 40 years which is mainly due to the gas and electricity used – the GWP impact for gas use over 40 years is estimated at 3,810 tonnes or 24.8 kg CO_2 eq./m^2 yr. and that for electricity use at 93.4 tonnes or 0.6 kg CO_2 eq./m^2 yr. This compares to Henderson and Young (2008) who found that individual solar thermal systems with gas boilers used for both space and water heating produced CO_2 emissions of 24.28 kg CO_2 eq./m^2 yr.

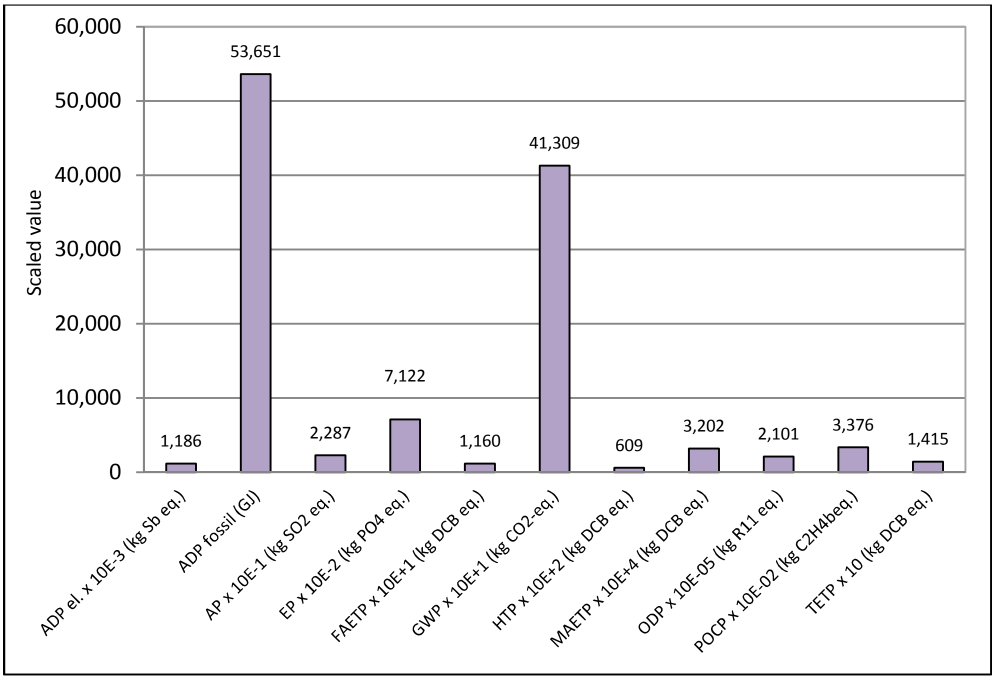


Figure 56 Life cycle environmental impacts for the combined solar thermal and gas system over a 40 year period.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

Natural gas burning in individual boilers is dominant particularly within the ADP – fossil (94%), GWP (94%) and ODP and EP both at (68%) - Figure 57. Contributions to the EP indicator appear through the use of natural gas and the associated emissions to sea water during the production of natural gas. Important impacts emerge from raw material extraction and the manufacturing process reflected in FAETP and HTP (85%), and TETP and ADP elements over 90%.

Contribution of other parts of the life cycle when operational gas and electricity is removed from the results is shown in Figure 58. The higher impacts are derived chiefly from: the apartment wet system, apartment storage cylinder and the solar thermal array. The substantial use of copper and steel for piping and radiators within the wet system contributes to impacts in all indicators ranging from 11.7% to 34%. The apartment storage cylinders exhibit similar impacts to those described for the electric panel, storage and district heating systems. The solar arrays used provide contribution impacts particularly in the MAETP 43.5% and AP 20.3% indicators.

Where solar thermal systems exist for water heating they are often used in combination with gas boilers as described above or electricity using electric panel and storage heaters or ASHP. The comparison of the environmental life cycle impacts of the solar thermal gas and solar thermal electric panel system using the same energy demand over the 40 year period are shown in Figure 59. The impacts for the electric based system are on average 70% more than those for the gas based solar thermal system and reflect the reliance of current electricity generation on fossil fuels.

Finally, the contribution analysis of the life cycle stage illustrate that operational gas supplied provides the major impacts for this system recognising that solar thermal provides a measured level of energy input for water heating. Component impacts are obtained from the space heating wet system, hot water storage cylinders and the solar collectors.

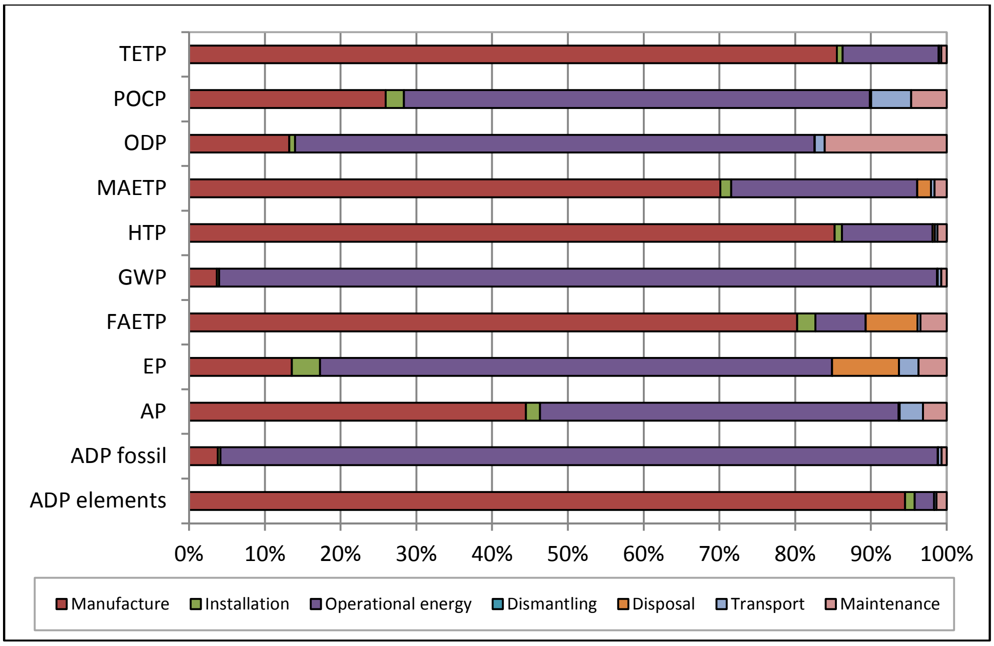


Figure 57 Contribution analyses for the combined solar thermal and gas system (incl. operational energy) over a 40 year period.

[Raw materials and manufacture are combined].

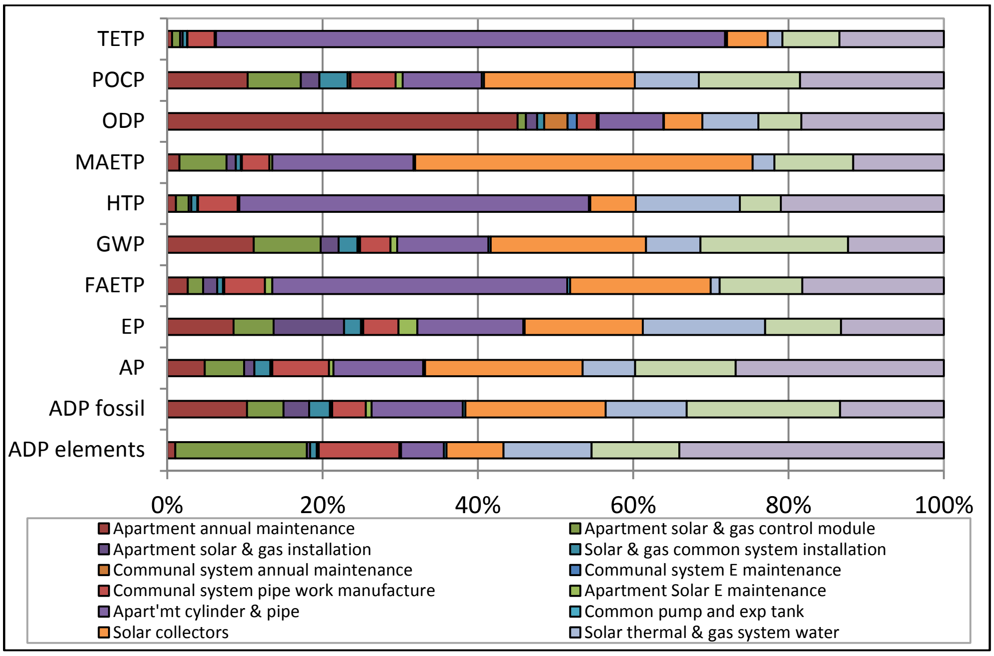


Figure 58 Contribution analysis for the combined solar thermal and gas system (operational energy removed) over a 40 year period.

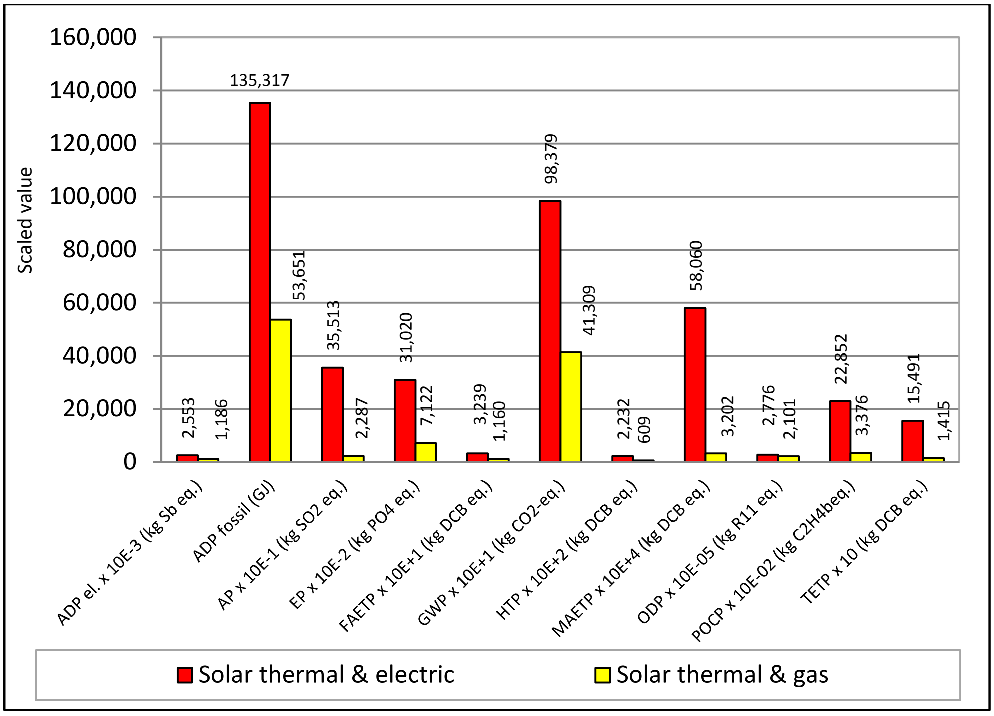


Figure 59 Comparison of environmental impacts of solar thermal gas boiler system with solar thermal and electric panel system.

4.1.12 Discussion of the heating system assessment

4.1.12.1 Overview of the results

The life cycle environmental impacts of the eight case study systems are shown in Figure 60 which includes the operation energy and Figure 61 which depicts the impacts without the operational energy included. The electric panel and electric storage systems have the greatest impacts and the solar thermal and gas boiler system the lowest impacts for majority of categories when operational energy is included. Across the eleven environmental indicators, the electric systems (panel, storage, combined and ASHP) are on average 2.5 times higher than the low-electric dominant systems (gas boiler, solar thermal and gas, district heating and community CHP systems) respectively. For all eight systems, the highest contribution to the impacts is from the electricity and the gas used during the operation stage. Operational contributions across the indicators range as follows where a 'smaller range' shows a greater influence from the operation stage:

- Electric panel system: 65.1% to 98.9%
- Electric storage system: 70.1% to 99.0%
- ASHP system: 46.9% to 98.1%
- Gas system: 3.8% to 97.2%
- Combined system: 52.8% to 98.9%

- District heating system 13.0% to 97.0%
- Community combined heat and power system 0.76% to 70.6%
- Solar thermal and gas system 2.6% to 94.4%.

The electric storage and panel systems have the greater GWP at 12,014 tonnes and 11,449 tonnes CO_2 eq. over 40 years respectively again due to their reliance on the UK grid electricity. The gas systems generally have the lowest GWP compared to the others at 4,131 tonnes CO_2 (Solar thermal and gas boiler) and 4,285 tonnes CO_2 (Community CHP system) over 40 years. Further comparison of the remaining environmental impacts shows that electric systems have the highest impacts for all indicators. Where impacts from the manufacture, installation, maintenance and disposal stages are considered they generally reveal comparable system impacts for POCP, GWP, AP and ADP elements. The electric systems dominate the remaining impacts except for ODP and ADP fossil where moderately higher impacts are shown for the gas system. The components of each heating system that offer the largest overall impacts are summarised in Table 13.

Table 13 Components offering largest overall impacts within each system type.

System type	Components offering largest overall impacts
Electric panel system	hot water storage cylinders electric panel heaters panel electronics
Storage heater system	hot water storage cylinders electric storage heaters
ASHP system	hot water storage cylinders wet system air source heat pumps
Gas boiler system	wet system gas boilers on-going maintenance
Combined gas and electric system	electric panel heaters centralised boilers centralised hot water supply system
District heating system	wet system hot water storage cylinders centralised gas boilers
Combined heat and power system	cogeneration components wet system hot water storage cylinders
Solar thermal and gas system	wet systems hot water storage cylinders solar thermal panels

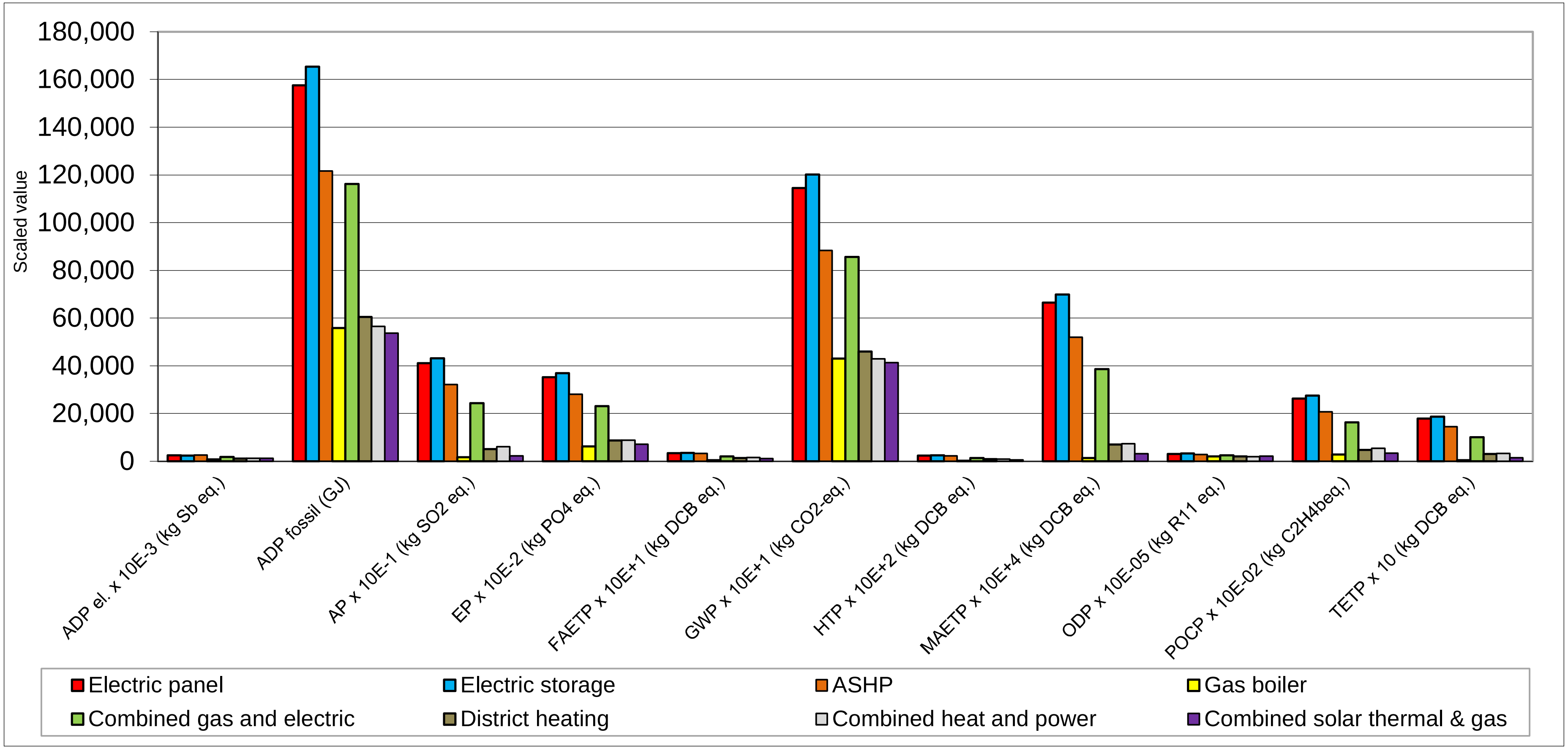


Figure 60 Comparison of environmental impacts of heating and cooking systems for heat generated over a 40 year period (incl. operational energy).

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

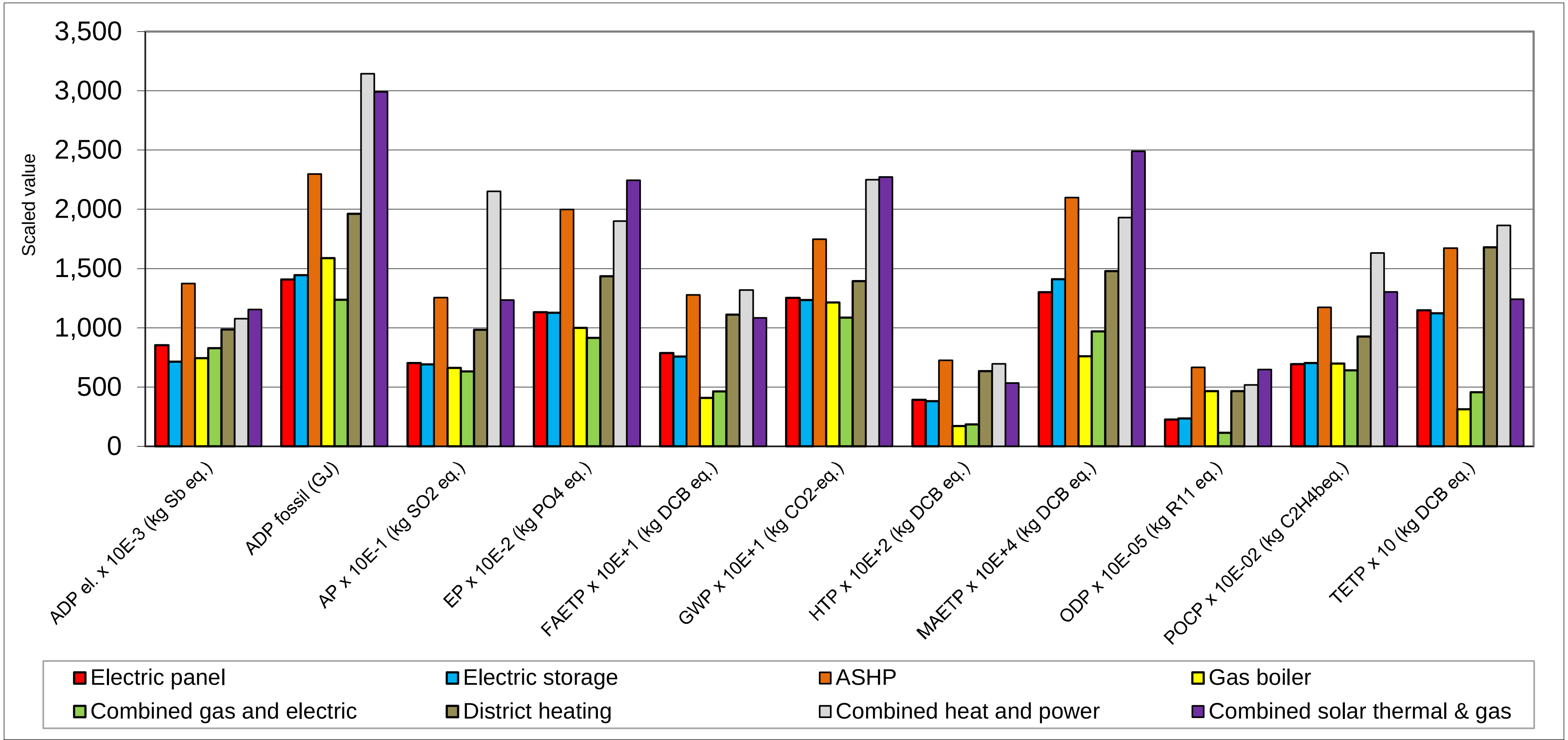


Figure 61 Comparison of environmental impacts of heating and cooking systems for heat generated over a 40 year period (operational energy removed).

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

The following section provides a brief overview of the main environmental burdens and the elements within the eight heat providing systems contributing to the environmental impacts.

4.1.12.2 Contribution analysis - based on impact indicator

ADP – elements and fossil: The depletion of elements ranges from 0.00773 t Sb eq. for the gas boiler to 0.02592 t Sb eq. for the ASHP and 0.025 t Sb eq. for the panel system. The major contributor to the electric system emissions is the production of electricity contributing approximately 53% for the ASHP and panel heater systems. The ASHP system gives non-renewable elements emissions (37.1%) from the depletion of copper and molybdenum in the production of the ASHP unit itself and the wet system and extra electric system components.

The ADP fossil is estimated the lowest at 53,650 GJ for the solar thermal system and the highest at 165,428 GJ for the electric storage system - this being almost totally from the operation stage through the depletion of natural gas and hard coal for electricity production.

AP: The storage heater system has the highest AP and the gas boiler the lowest, detailed as 43 and 1.6 t SO_2 eq. respectively. Major contributors for both systems are emissions from electricity generation (98.4%) and natural gas combustion (60.9%) respectively. However, the manufacture of the central heating wet system contributed 19.5% to emissions through the energy used in the extraction and processing of copper and steel for the pipes and radiators.

EP: Contributions to the EP indicator are highest and similar for the storage and panels heating systems at 3.6 t PO_4 eq. This principally relates to emissions (96.8%) from electricity generation. The lowest at 0.06 t PO_4 eq. is the gas boiler predominately with emissions from natural gas combustion (83.8%) but significantly, the gas boiler, installation and wet system contributed a further 11.7%. Significant contributions are also seen in the ASHP and solar thermal system components, again through the extensive use of copper and steel in their systems.

FAETP: Emissions from electricity generation and gas combustion range from 48.5 t (gas boiler 15.9%) to 347 t DCB eq. (storage heater 77.7%). Interestingly, the copper based wet system contributed 40.6% of emissions for the gas boiler derived from the steel used for radiators and copper for the pipes and connections. Elsewhere, within the electric systems, the use of stainless steel in the storage cylinder particularly impacts the FAETP indicator, offering contributions of 52%. The electric heating panels also exhibit impacts to the FAETP, at 23% - this again is attributable to the steel used in manufacturing.

GWP: The solar thermal & gas boiler offers the lowest carbon equivalent emissions at 4,131 t CO_2 eq. and the panel and storage heater systems the highest at 12,014 t CO_2 eq. The production of electricity and the combustion of gas are the main contributors to GWP at 98.9% and 97.1% respectively but with the production of collectors and boilers for the solar system and cogeneration components for the CHP producing air emissions derived from fossil fuel utilization and its energy intensity.

HTP: Again the gas boiler offers the lowest emissions at 246 t DCB eq. with the storage and panel heater the highest at 2,500 t DCB eq. The main impacts for the electric systems derive from the generation of electricity (85%) and from the use of stainless steel particularly in the hot water storage cylinders. Highest overall HTP impact after operational energy is removed is the ASHP system (725 t DCB eq.) – however similar impacts are experienced by those using wet systems.

MAETP: The overall impacts range from 136,200 t to 6,987,500 t DCB eq. for the gas boiler and storage heater respectively. Approximately 50.0% of the gas boiler emissions were due to the manufacture of the individual gas boilers and the wet systems particularly through the extensive use of steel in boilers and the powder coating for the boiler covers. The solar thermal system has the highest MAETP impact when the operational energy is removed – this is predominantly due to the solar thermal collectors and specially the aluminium, copper and steel used in their manufacture.

ODP: The storage heater has the highest emissions at 0.000323 t R11 eq. and the community CHP system the lowest at 0.000193 t R11 eq. However larger construction and maintenance ODP impacts are experienced by the wet based systems reflecting the halogenated organic emissions to atmosphere through the use of PTFE sealing tape on pipe fittings.

POCP: The POCP emissions range from 4.57 t for the gas boiler to 186 t C_2H_4 eq. for the storage heater system. The majority of impacts are through electricity generation and the emissions of NOx and VOC. In the gas boiler system approximately 24% of emissions are derived from the use of energy in copper, brass and steel manufacture and the release of NMVOCs. Elsewhere, highest non-operational energy impacts are from the community CHP system especially from the common components of the CHP unit.

TETP: The gas boiler system offers the lowest impacts at 4.57 t and the electric storage system providing 187t DCB eq. For the electric systems, the majority of impacts (93%) are derived from the production of electricity. For the gas boiler system, approximately 68% of system component impacts predominately come from heavy metals to the air including: arsenic and chromium especially relating to the wet heating systems metals. Impacts from the community CHP system include TETP at 48.0% of system component impacts and mainly from the metal used in the cylinders, wet system and heat stations.

4.1.13 Hot spot analysis

From the results of the assessment a number of hot spots are identified that require further analysis and exploration, these include: disposal, installation of systems, maintenance and servicing impacts and changes to the space heating to water heating ratio. In addition, the analysis demonstrated the sizable impacts of the wet heating system (ASHP, gas boiler, district heating, CHP and solar thermal systems) and hot water storage cylinders (Electric panel, storage, ASHP, district, CHP and solar thermal systems) - these aspects are now explored further.

4.1.13.1 Disposal

The Energy Using Products (EuP) programme seeks to improve the environmental performance of new products through better characteristics and appropriate methods in design (ENER, 2010). At the other end of a products life, the EU waste framework directive (EU, 2008) provides the overarching legislative structure for the collection, transport, recovery and disposal of waste. Directives focus on hazardous wastes, electrical and electronic equipment and packaging amongst others (EC, 1994; UKGOV, 2005; EU, 2003).

The metals sector in the UK is traditionally one of the most profitable recycling industries, with an estimated turnover of between £4 billion and £5 billion a year (BMRA, 2011). Anecdotal evidence for the dismantling and waste management of heating equipment and systems show that generally, for apartment blocks, the metal is scrap recycled – this is especially true for copper, aluminium and steel products which form the majority of the system components. Recycling rates used in these calculations are those previously mentioned in the assumptions section, however, recycling rates may well be more than those stated considering current scrap metal demands and heating systems being predominately material heavy providing for recycling during replacement activities and at the end of the overall systems life. The impacts of recycling credits of the eight systems are shown in Figure 62.

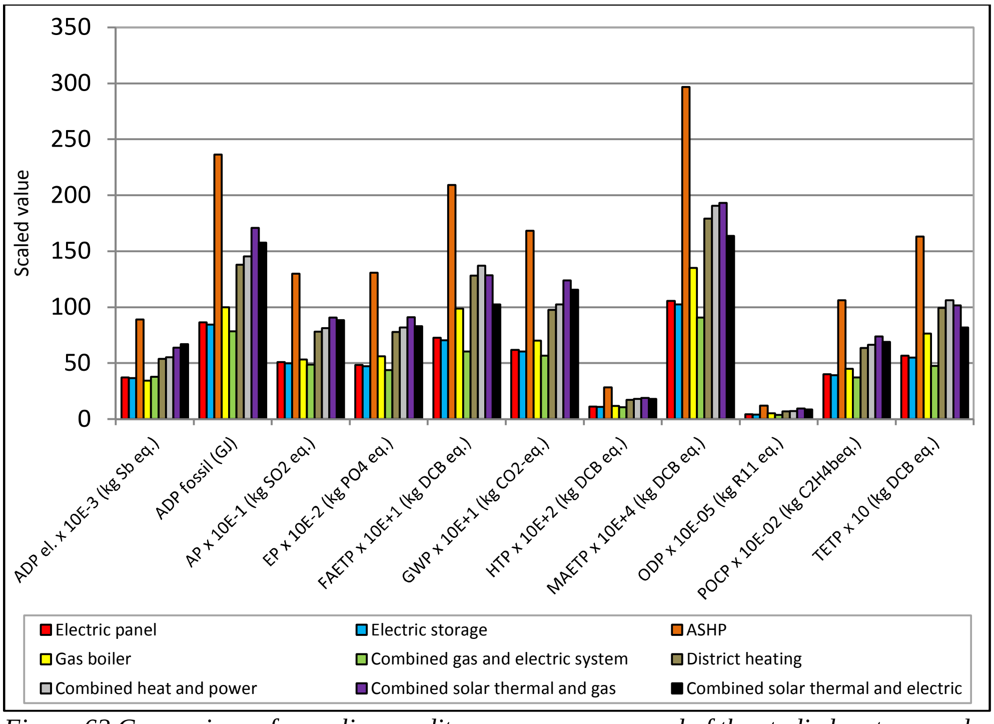


Figure 62 Comparison of recycling credits as energy consumed of the studied systems and components.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

When recycling of steel and iron, copper, aluminium, zinc and nickel system parts is considered in the LCA process; there is an overall reduction to GWP of between (4.8% – 9.6%) and for ADP elements and ADP fossil by (2.45% - 5.1%) and (6.5% – 13.5%)

respectively compared to uncontrolled disposal. This is most prominent in the: ASHP, gas boiler, and CHP and district heating systems where water storage cylinders, wet heating systems and supply systems are extensive and materially heavy.

4.1.13.2 Installation

Heating and cooking systems for high rise apartment blocks using individual gas connections are typified by extensive pipe networks and construction works to accommodate them safely within or external to the building. Requirements specifically for gas safety include; good ventilation, fire resistant coverings and escape route considerations (CORGI, 2007). Installation impacts (see Table 14 and Figure 63) are relatively minor when compared to overall environmental impacts, on average only 2.07% for the district heating and CHP systems to 0.11% and 0.08% for the electric panel and storage systems again this is due to the extent of construction works to facilitate pipe-work and energy centre installation.

Table 14 Installation impacts as an average across all environmental indicators.

System type	Installation impacts
Electric panel	0.11%
Storage heater	0.08%
ASHP	0.19%
Gas boiler	1.75%
Combined gas and electric	0.33%
District heating	2.07%
Combined heat and power	2.06%
Solar thermal and gas	1.44%

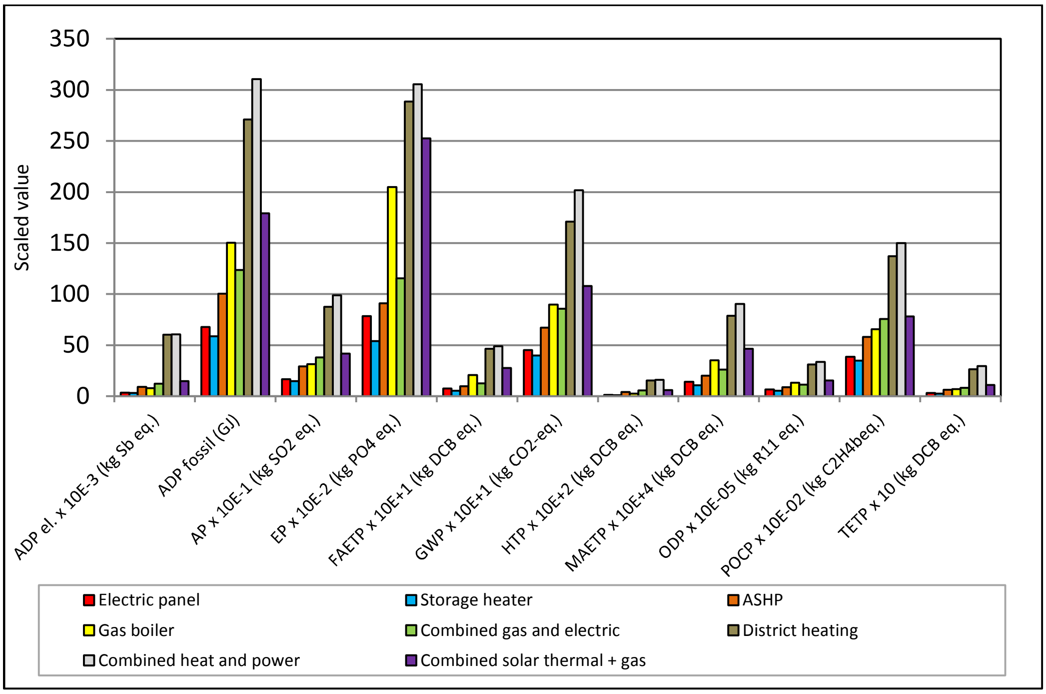


Figure 63 Impacts from the installation for each of the studied systems.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

4.1.13.3 Maintenance and servicing impacts

Regulations and guidelines dictate the levels and periods for on-going testing for each heating system type (HSE, 2009); this is especially important where apartments are either privately rented or part of social housing. Landlords are legally compelled to service and test gas appliances in rented homes yearly and must produce an annual gas safety certificate (GSR, 2011). For centralised gas fuelled systems, there are fewer requirements concerning servicing, however, good practice suggests annual inspection and servicing (EST, 2004); whereas Landlord's electrical inspection reports are not obliged by law but are recommended and mainly consider portable equipment, wiring and sockets (Elliott, 2008; IEE, 2008). Overall, maintenance GWP impacts are approximately 4.0 times higher for the gas related systems (solar thermal, gas boiler, and CHP) than for the electric based systems - see Figure 64.

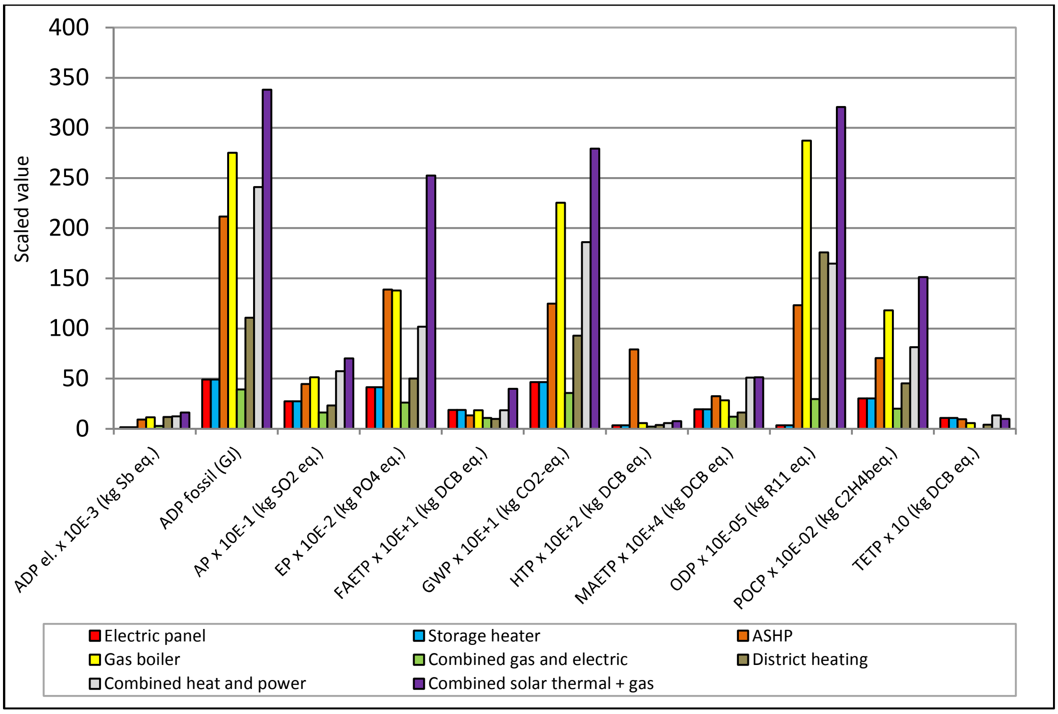


Figure 64 Maintenance impacts for the eight studied systems.

[The values for the impacts have been scaled to fit. Original environmental impacts can be obtained by multiplying the values shown on the y-axis by the scaling factor given in brackets].

Increasing the service intervals to five yearly on the gas system would reduce impacts and bring them into line with the other systems, however, this would require changes in gas service practice. Using combined systems minimises the overall block service requirements due to longer service intervals and there being fewer boilers to service (EST, 2004).

4.1.13.4 Wet heating system and hot water storage

The installation of the wet systems using copper pipes, connectors and steel radiators has shown to impact on five out of the eight studied systems. Further exploration to reduce such impacts suggests the use of under-floor space heating. Where this type of wet system can be installed there is a possible average reduction of 60% across impact indicators – see Figure 65. However, practical installation constraints exist especially for existing properties but the ASHP system performance improves with the lower operating temperatures and under-floor heating.

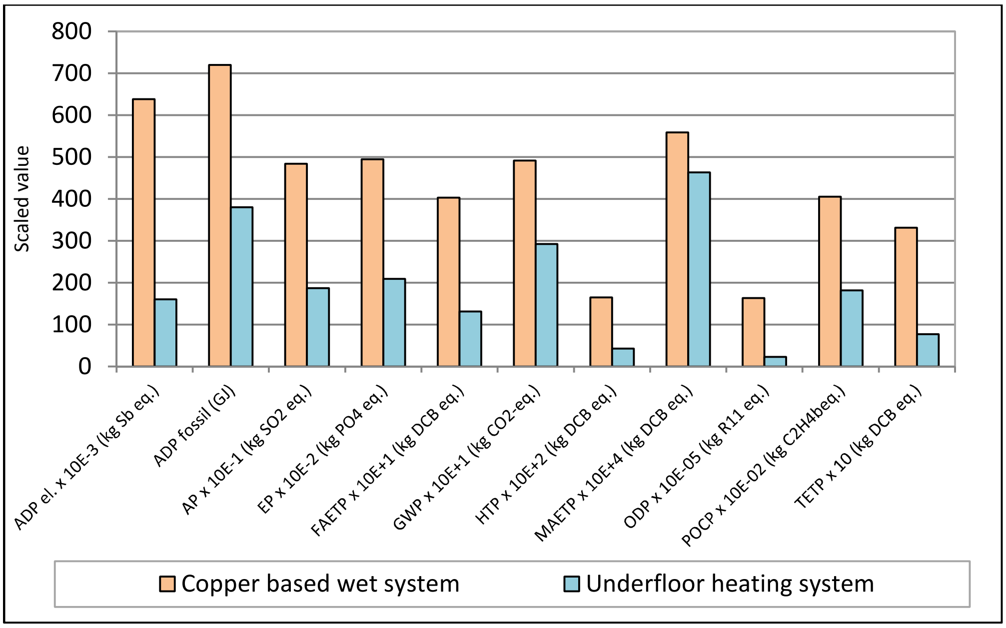


Figure 65 Impacts between a copper wet system and an under-floor heating system.

Hot water storage impacts are experienced by systems using stainless steel and copper storage cylinders (panel and storage heater systems, district heating and CHP). Although the impacts are relatively small across the range of indicators, the impacts on energy supply can be significant – see Figure 66.

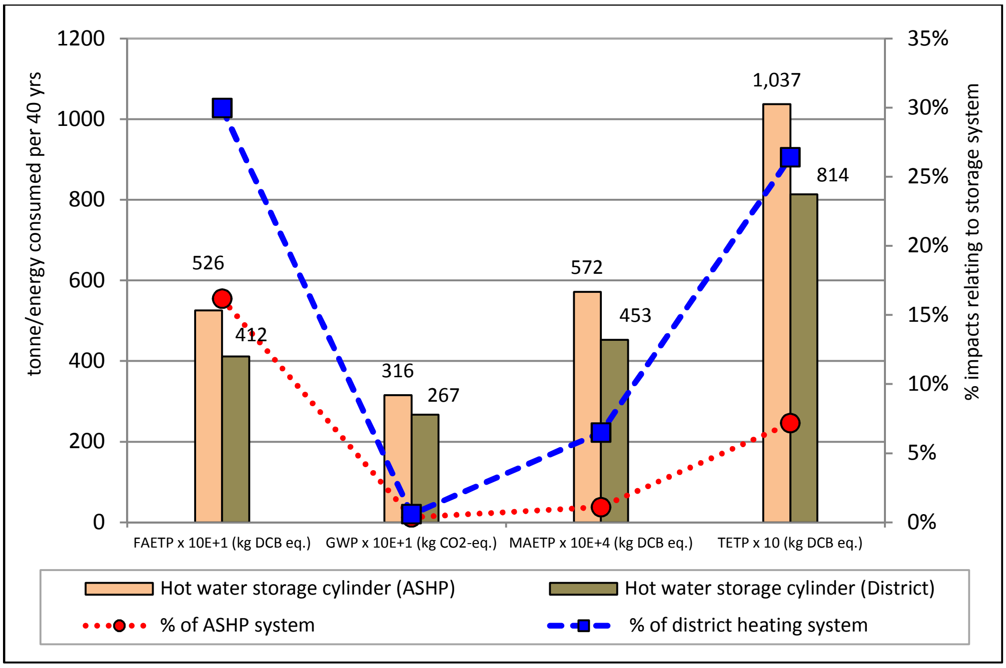


Figure 66 Higher environmental indicator impacts for hot water storage cylinders for two studied systems when compared to overall system impacts.

4.1.13.5 Energy usage from water and space heating demand changes

As discussed previously, there is an increasing demand for household hot water while improvements to insulation and other efficiency advances have reduced space heating demand; however, hot water is very dependent on individual users' habits. Average cooking energy demand is less than 7% of the overall energy supplied to each apartment. Electrification of cooking through the uptake and use of electric only appliances such as electric hobs, electric ovens and microwave ovens, could add an additional 73 GJ primary energy per apartment over the 40 year period, however, again this is moderate compared to the hot water and space heating requirements.

To identify the impacts of any change to the space heating to water heating ratio for the case study systems, the heat demand scenarios shown in Table 15 were studied. Changes are made to the energy demand first through an increase in water heating over space heating using the functional unit of the study (scenario a & b) and second by increasing overall demand for water and space heating (scenario c & d).

Table 15 Energy demand scenarios per system per annum (kWh/m^2 yr.).

Scenario	Space heating (kWh/m^2 yr.)	Water heating (kWh/m^2 yr.)
a) Low space heating demand	50	59
b) Case study apartment block demand	59	50
c) Higher space heating demand	103	140
d) High case study apartment block demand	140	103

The impacts of reducing the space heating demand while increasing hot water demand on the system for the studied scenarios is shown in Figure 67.

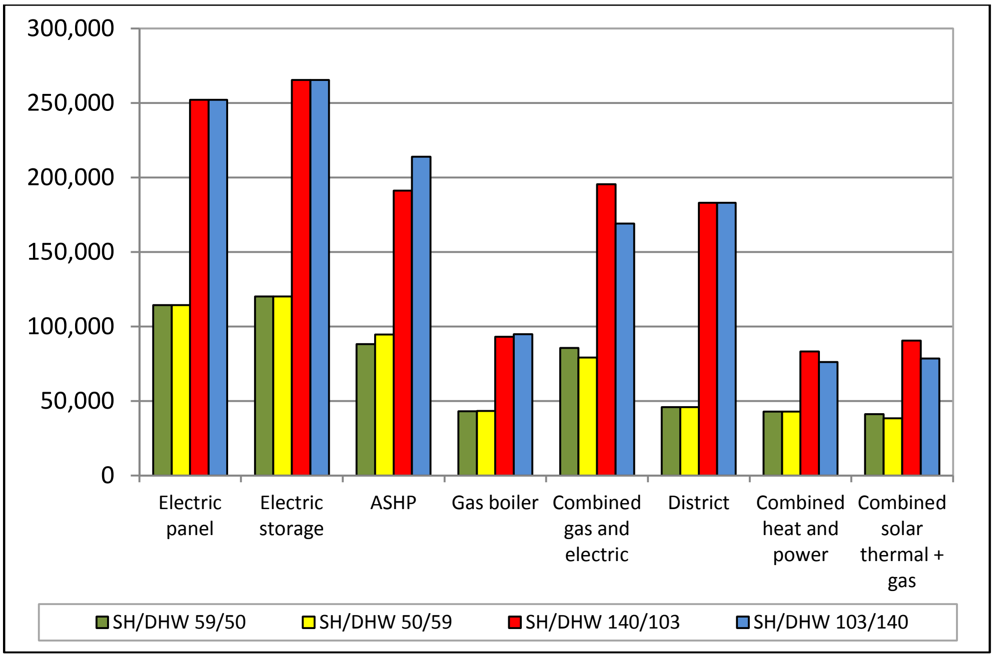


Figure 67 Change in GWP impacts associated with an increase in use of energy for domestic hot water.

Results for the gas boiler system show a slight increase in GWP by 4.4%. Since combination boilers tend to be more efficient when providing space heating, the results reflect this inefficiency. Increases are also experienced by the ASHP system (10%) – this through the use of immersion heaters for water heating. Improvements are seen for the combined system, solar thermal and CHP system. The combined system shows larger impact reductions of 8.3% showing improved performance through greater use of centralised gas hot water and a reduction in the use of high carbon electricity. The solar thermal system provides more of the demand than the gas boiler and the CHP system benefits from apartment water storage.

4.1.14 Life cycle emissions from the electrification of heat in cities

Domestic heat demand currently represents 85% of total domestic energy use with the majority of this heat being delivered by gas through individual gas boilers using central heating systems (ICEPT and CES, 2010). It is also recognised that in the past, gas central heating has played an important role in improving residential temperatures (Shorrock, 2008). However, the size and shape of gas use in cities particularly city centres appears to differ. The projected growth in the use of electricity for heating and cooking in cities particularly where dense housing is planned or predominates could have significant environmental impacts. The following considers such implications based on life cycle emissions and the electricity productions mixes outlined previously. For this study, consideration is given to the current pattern of electrification in Manchester, where more than 260 apartment blocks are located within the city centre, and makes the hypothetical assumption that it is also similarly experienced in the 20 largest populated cities in England, see 17 Appendix 7. The existing number of apartment blocks in Manchester and its population are therefore compared to the population of the other twenty cities to determine relative apartment block and subsequently apartment numbers.

First, assuming the case where other major cities in England follow a 100% switch to any of the eight studied systems over a 40 year period to 2050 - the approximate environmental impacts would be those as given in Figure 68. The total estimated GWP from using electric heating[7] systems at the 2010 electricity mix is on average 94 Mt CO_2 eq. 40 yr. The equivalent emissions from the gas fuelled[8] systems would be 38 Mt CO_2 eq. 40 yr. providing savings of nearly 60%. For all other indicators the gas fuelled systems provide savings (many substantial) over the electric based heating systems. When the life cycle impacts are estimated for the current[9] heating systems found in cities, the impacts calculated are those shown as 'city average emissions 2010' in Figure 68.

[7] Electric heating systems include: panel, storage and ASHP.
[8] Gas fuelled systems include: gas boiler, district heating, CHP systems and solar thermal system.
[9] Current heating systems refers to the Manchester apartments survey where electric heating, gas heating and combined systems were estimated at: 80%, 14% and 6% respectively.

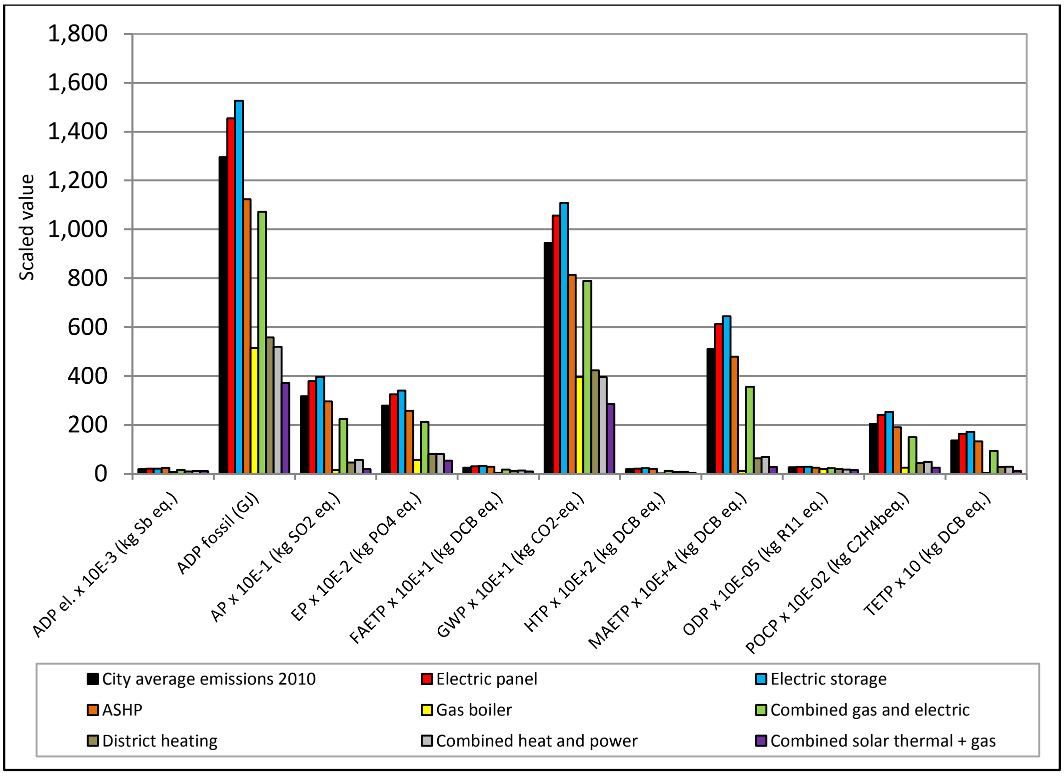


Figure 68 Comparison of environmental impacts of heating and cooking systems for heat generated from housing in 20 major cities in England [Environmental impact (Mt/energy consumed per 40 years].

Second, given the possibility of the decarbonisation of the electric system between 2010 and 2050 to planned levels (CCC, 2008), emissions for 2050 suggest that electric based heating systems could produce only 10 Mt CO_2 on average compared to the gas fuelled systems at 33 Mt CO_2 in 2050 – see Figure 69. Overall, this shows a major reduction in CO_2 emissions from electric based systems and a small reduction for the gas based systems.

In terms of the best system presently from an environmental perspective for heat within cities based on the assumptions and limitations stated, the solar thermal and gas based system is first. The electric based systems perform the worst based on the current high use of fossil fuels within the electricity mix. However, when considering the planned decarbonisation of electricity and impacts, then the communal based ASHP with electric immersion heating comes out best.

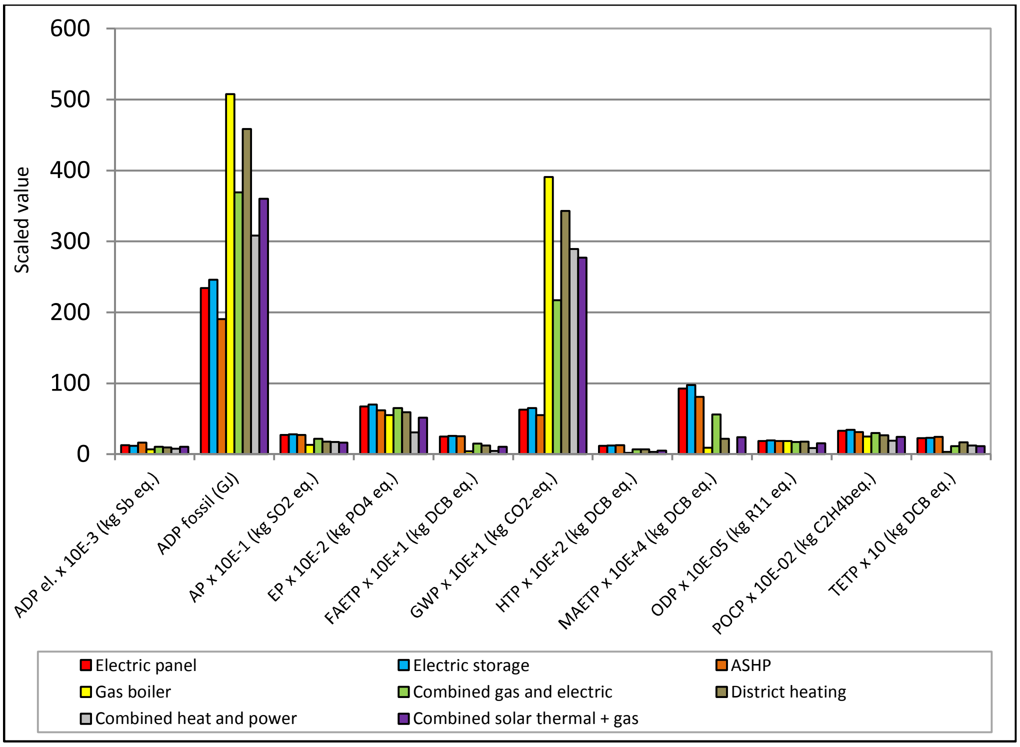


Figure 69 Comparison of environmental impacts of heating and cooking systems for heat generated from housing in 20 major cities in England (using a low carbon electricity mix).

4.1.15 Summary

The sustainability results for the life cycle impacts of the eight heat providing systems can be summarised as follows:

- From the eight systems studied, the GWP impacts from manufacture, installation, operation and final removal are greatest for the all-electric systems - electric panel, electric storage and ASHP offering GWP impacts of 11,449, 12,014, 8,831 tonnes CO_2 eq. over 40 years respectively.
- The gas based systems - gas boiler, district heating, community CHP and solar thermal and gas offers GWP impacts of 4,306, 4,597, 4,298 and 4,131 tonnes CO_2 eq. respectively. The hybrid combined gas and electric system offers GWP impacts of 8,562 tonnes CO_2 eq. over 40 years.
- For all systems, operational energy used during the 40 year period provides the main environmental impacts.
- In terms of the life cycle components of the systems and their operation; the electric panel, electric storage, gas boiler and combined systems offer very similar impacts at 125, 123, 122 and 108 tonnes CO_2 eq. per system respectively. Higher component impacts are experienced by the district, ASHP, community

CHP and solar thermal and gas system at 140, 175, 225 and 227 tonnes CO_2 eq. per system respectively. The majority of impacts arise from the heavy use of ferrous and non-ferrous metals during component and system manufacture. The majority of metals used in all systems are both easily recyclable and in-demand; this therefore plays a role in reducing the environmental burden through system crediting.

- Installation impacts across all systems are minor compared to the overall impacts ranging from 0.08% for the electric panel to 2.07% for the district heating system using an average across all impact indicators.
- Maintenance GWP impacts are approximately four times higher for the gas related systems (solar thermal and gas, individual gas boiler, and CHP) than for the electric based systems and are due to strict requirements for the safe installation and continued use of gas supplies and gas using equipment.
- The impact of increasing hot water use against space heating shows increases for the gas boiler and ASHP systems and decreases for the combined gas and electric system, solar thermal gas and community CHP systems. This reflects the advantages and increased efficiencies of the more centralised heat supplies to apartments.
- The LCA results show that 94 Mt of CO_2 eq. 40 yr. could be generated by using electric only systems for heating in city households in England (using 2010 as the base year). If the decarbonisation of electricity took place to planned levels at the base year, life cycle impacts would be reduced to 10 Mt CO_2 eq. per 40 years.
- Electrification of heat is already well established in English cities; the majority using traditional electric resistance based technologies; an approach that suits predominately smaller well insulated homes. Reducing the share of high carbon producing fuels in the electricity mix or implementing CCS on such power stations could help to reduce the environmental impacts from the use of electricity for heating and cooking.

The life cycle impacts have been studied using LCA – now the direct impacts from indoor air quality monitoring are described.

4.2 Evaluation of environmental sustainability: Indoor Air Quality Monitoring (IAQ)

The previous chapter conducted the evaluation of environmental sustainability of the systems providing space, water and cooking heat using life cycle assessment (LCA). This chapter focuses on the direct air emissions and related environmental impacts associated with the indoor environment and heat providing systems. The chapter presents the results of indoor air quality monitoring (IAQ) for a number of typical homes in the UK that use either gas or electricity. The indoor air quality monitoring methodology used here has been described earlier in Chapter 3.

4.2.1 Goal and scope definition

The aim of this part of the research is to measure the quality of indoor environment associated with household gas and electric heat provision. Air monitoring units developed specifically for this research are used for these purposes. The specific objectives are:

- to measure the quality of the indoor environment associated with household gas and electric heating and cooking in urban areas;
- to record concentrations of ambient pollutants in real time over extended periods from household heating and cooking events;
- to identify similarities, differences and trends in indoor pollutants between gas and electric energy supply and combustion at the household level; and
- to identify the main impacts and issues that could arise from a change in the type of energy supplied to city residential homes i.e. electrification of heat.

The functional unit is defined as the ‘indoor kitchen and lounge emissions and the respective outdoor emissions’, measured and recorded over a 14 day period, for a range of urban domestic dwellings. The approach considers emissions primarily from cookers and cooking, heat providing systems, and secondarily from human and other emissions including sprays, cleaners etc. - see Figure 70.

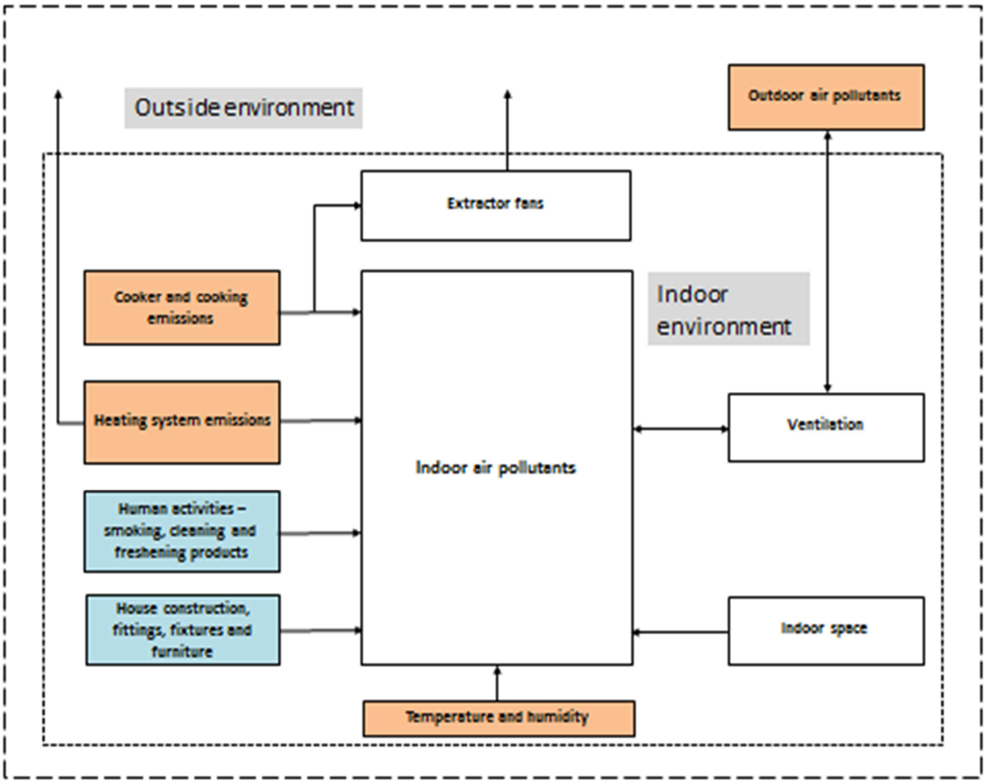


Figure 70 Air quality monitoring system boundaries and stages considered for domestic dwelling emission analysis.

[Primary emission sources shown in orange and secondary sources in blue].

4.2.2 Assumption and limitations

The main assumptions for the indoor air quality analysis (IAQ) case studies are as follows:

- The impact on indoor emissions from gas boilers used for space heating and hot water is assumed negligible when considering the external combustion gas flues properly installed and flows in each case (gassaferegister, 2011).
- The impact from electric space and water heating indoor emissions is assumed to be comparatively low to negligible (Arashidani et al., 1996).
- Results from pilot IAQ monitoring indicated only very small emission impacts for the selected indicators within the lounge/sitting rooms of the test homes. In addition, households found the sensor units to be disturbing and exhibited a tendency to turn the machines off, therefore further monitoring or analysis in this area was not conducted.
- The VOC element of the study is not performed here as this aspect is considered as not representative of impacts seen from the use of either gas or electricity for

heat provision in a home but one of kitchen cleaning products, cooking substances and the food being cooked.

- The indoor environment is a dynamic place rather than being static therefore the placement of the sensor units is important to ensure representative data. Sensors are placed between 1 m and 1.5 m from the ground and at least 1 m from walls and away from areas of direct ventilation (Crump et al., 2002). External sensors are placed at least 1.5 m from buildings; a typical layout is shown in Figure 71.
- Overall analysis is complex as there are many factors occurring at the same time within the environment - cooking (combustion and food pollutants), emissions from people, ventilation and sporadic occurrences (use of sprays, surface cleaners etc.). A broad assumption made is that during the winter - window and door ventilation is more restricted whereas during summer these would be essentially open especially during cooking periods. Extractor fans are fitted in all kitchens of the study homes – their use is unpredictable.
- A match is made between the indoor and outdoor sensor timings to ensure analysis encompasses activities occurring during the same period and times.
- Names assigned to the studied homes are not the real names but made for referencing only.
- Household diaries are used to establish any specific emissions or events that need to be considered when analysing data i.e. use of toasters, burning of food.

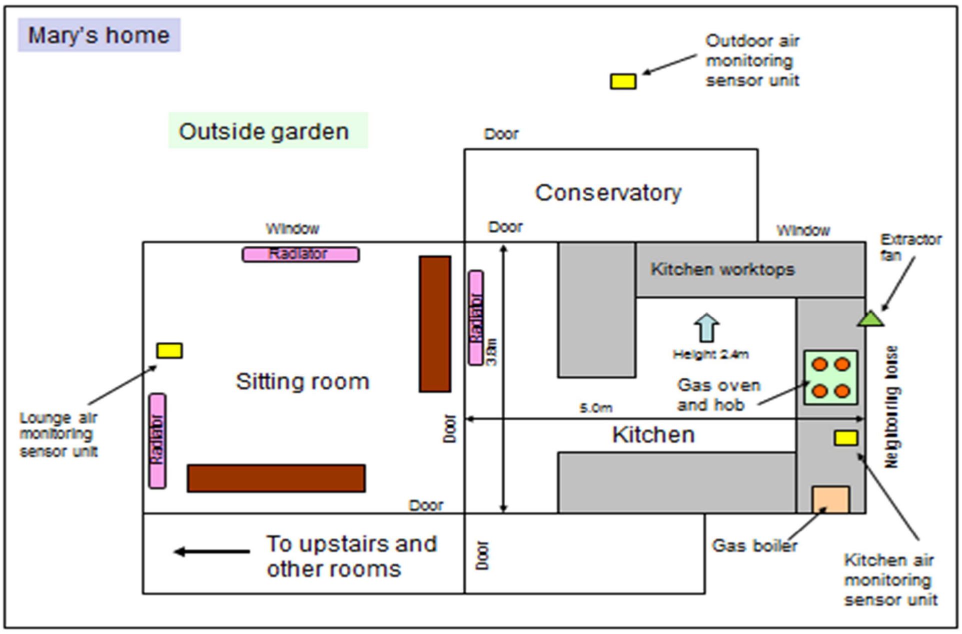


Figure 71 Typical placements of air sensor units within study homes.

[drawing not to scale].

4.2.3 Air quality monitoring sensors, data acquisition and studied homes

The construction and use of the air quality monitoring sensor units was described earlier in Chapter 3 – further description of the units and indoor air quality methods can be found in 18 Appendix 8. Prior to any monitoring, the sensor units were calibrated and checked for correct functioning of the sensors and associated electronics. Checks and tests were conducted against known gas concentrations - see Table 16; results were analysed to ensure conformity - see Figure 72. An important observation from this figure is the interaction and temperature corrections between several of the sensors; SO_2 is affected by NO_2, and SO_2 is affected by the CO sensor. This has been considered within the calibration coefficients. The CO sensor is the fastest to respond to changes in ambient concentrations.

Table 16 Calibration gas concentrations used for air monitoring sensor tests.

Calibration gas	Concentration (ppm)	Tolerance (%)
NO_2	0.957	+/- 2%
SO_2	1.17	+/- 2%
CO	103	+/- 2%
CO_2	4976	+/- 2%

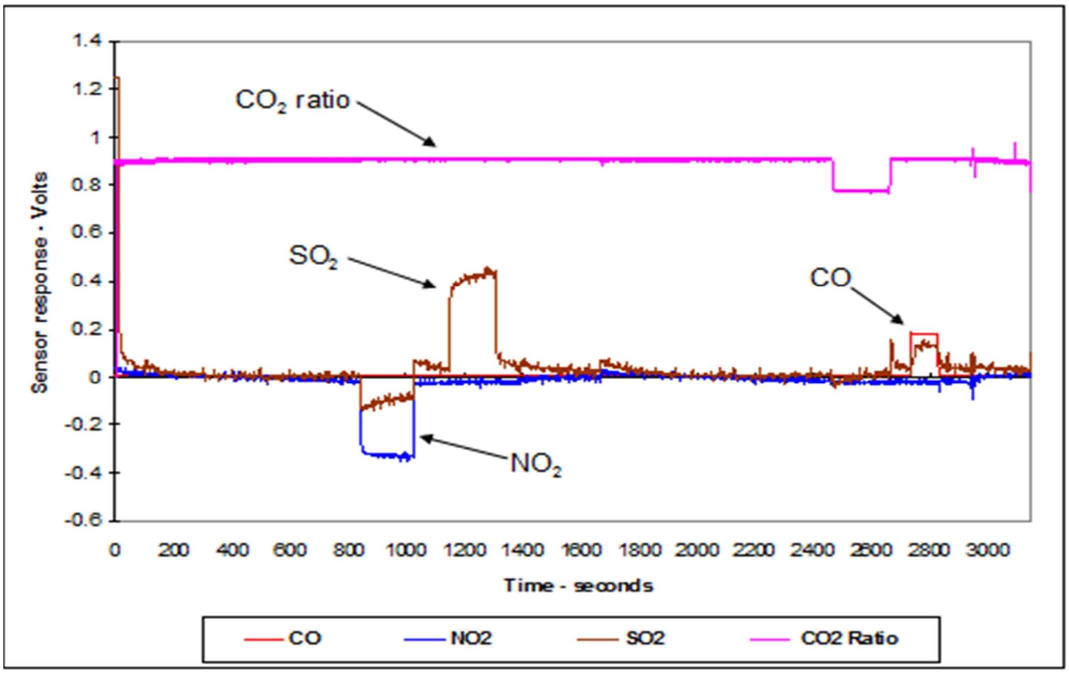


Figure 72 Calibration results from an example air monitoring sensor unit.

Monitoring was planned initially with households living in houses and apartments; generally this lasted 14 days each season with data collected during the summer and winter. In order to ensure that both gas and electric systems are represented, households were selected that use one or the other system and a note taken specifically of their cooking system i.e. electric/gas hob and/or oven. Overall nine homes were monitored - see Table 17.

To enable monitoring to focus predominately on cooking and heating events, there was a requirement for the occupants to be non-smokers and the use of barbecues and candles to be minimised during the monitoring period. Three air quality sensor units were planned to be placed in the selected homes; one unit in the kitchen, the second in the lounge and a third outside of the house or apartment. Importance was given to ensuring that units are in representative locations and not disturbed by unrelated emission sources. A variety of heating and cooking types were observed within the monitored homes - see Table 18. Outside sensors were sheltered from the elements but able to take samples in free air.

At the end of the 14 day period, the units were removed and returned to the laboratory for assessment and downloading of the acquired data. In addition to the installed units; occupants were asked to complete a simple diary showing any significant cooking or heating events during the 14 day monitoring period – 18 Appendix 8.
Data was acquired over two different seasons; winter and summer - this enabled any contrasts to be observed between the summer (when there could be greater ventilation from outside) and the winter (with lower outside ventilation).

Table 17 Homes monitored for indoor air quality during 2011.

Location and type of homes monitored	Number of homes monitored	Period monitored
London:		
Semi-detached	1	February – March 2011
Flats/Apartments	3	February – March 2011
Manchester:		
Detached	1	July – August 2011 November – December 2011
Semi-detached	3	July – August 2011 November – December 2011
Flats/Apartments	1	July – August 2011 November – December 2011
Total:	9	

Table 18 Heating and cooking energy within studied households.

Heating and cooking combinations	Households monitored
Gas central heating	6
Electric panel/storage heating	3
Electric only cooking	3
Gas only cooking	6

Although a range of homes have been studied as described above; for this specific analysis only four are considered in detail; these are shown in Table 19 along with home construction and insulation details. These have been chosen due to the range of data originally acquired, their use of gas or electricity for cooking or a combination of both, along with their proximity for follow-up monitoring activities.

Table 19 Specific homes used in results analysis including construction and insulation details.

Studied home	Cooking combination	Space and water heating	Home construction details	Home insulation standard
Mary 'all gas' home.	Gas oven and gas hob.	Wall mounted older style non-condensing gas boiler, radiators and hot water storage cylinder.	1980's brick built tiled former local authority end of terrace house.	Cavity wall and loft insulation UPVC double glazing Conservatory reducing door ventilation or leakage.
Madelief 'all electric' home.	Electric oven and electric hob.	Electric storage heaters and immersion heaters in water storage cylinder.	2000's brick built apartment – 1st floor level.	Cavity wall and loft insulation UPVC double glazing.
Margaret 'all electric' home.	Electric oven and gas hob.	Wall mounted modern condensing gas boiler, radiators and hot water storage cylinder.	1930's brick built and tiled semi-detached house.	Loft insulation – kitchen extended and cavity wall insulated UPVC double glazing Conservatory reducing door ventilation or leakage.
Desmond 'all electric' home.	Electric oven and electric hob.	Wall mounted older style non-condensing gas boiler, radiators and hot water storage cylinder.	1970's brick built former mid terraced house.	Loft insulation fitted but not cavity wall UPVC double glazing Conservatory reducing door ventilation or leakage.

4.2.4 Inventory analysis and results

Overall, 240,000 data points were obtained during the monitoring campaign. A variety of statistical methods available in the SPSS and the principal component analysis (PCA) tool within the Community analysis package (Manfren et al., 2010) software packages have been used to analyse the data: i.e. summary statistics, tests of variance between different pollutants, etc. The analysis considers the impacts of seasonal changes, ventilation and the type of household energy used.

4.2.4.1 Indoor/outdoor concentrations

Figure 73 and Figure 74 show the indoor and outdoor concentrations of CO for an 'all gas' (Mary's house) and an 'all electric' (Desmond's house) during the summer and winter. The majority of CO concentrations for the 'all gas' house are higher indoors as would be expected with the use of gas cooking appliances – this applies to both the summer and the winter periods with maximum levels of 5.9 ppm and 13.4 ppm respectively. Outside concentrations for the 'all gas' house are moderately the same for both seasons with averages of 0.25 ppm summer and 0.74 ppm winter. The 'all electric' house shows lower overall levels of CO within the kitchen with similar levels both during the summer and the winter – maximum levels are 3.31 ppm during summer and 1.82 ppm in winter. In a similar manner, the majority of NO_2 concentrations are higher in the indoor environment – reflecting the confined space of the kitchen, lower ventilation, and possible emissions from the use of gas for cooking. As would be expected for summertime, the highest temperatures are found within the indoor environment. The indoor/outdoor temperature graph exhibits a smooth changing shaped due to the relatively slow changes of temperature over the monitoring period.

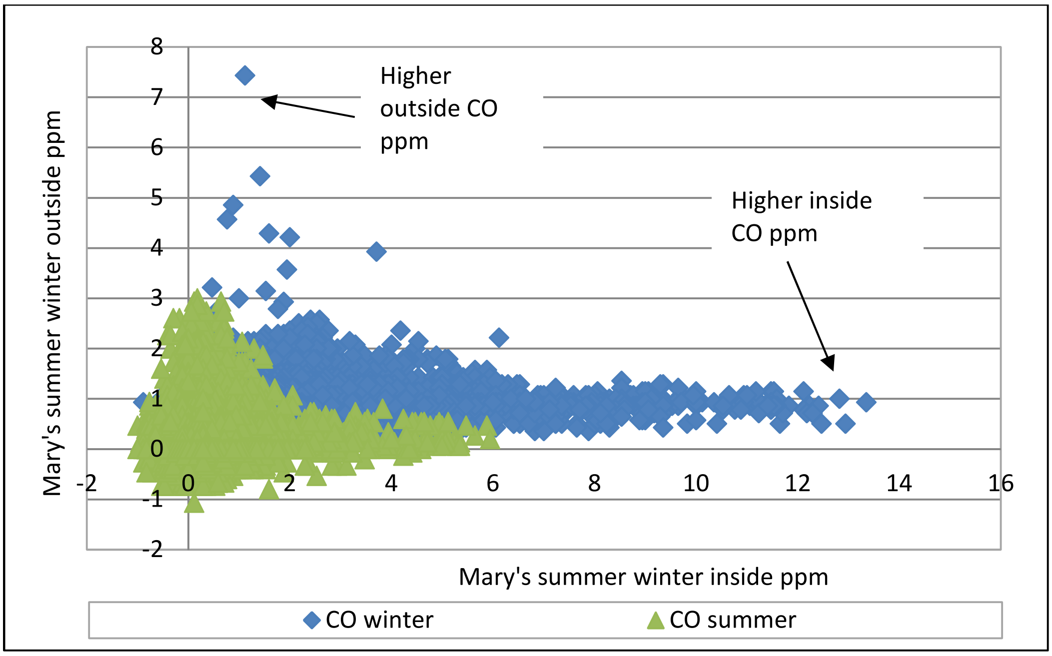


Figure 73 Kitchen and outdoor CO concentrations during summer and winter for an 'all gas' home'.

[Note relative higher concentrations in kitchen during the winter period].

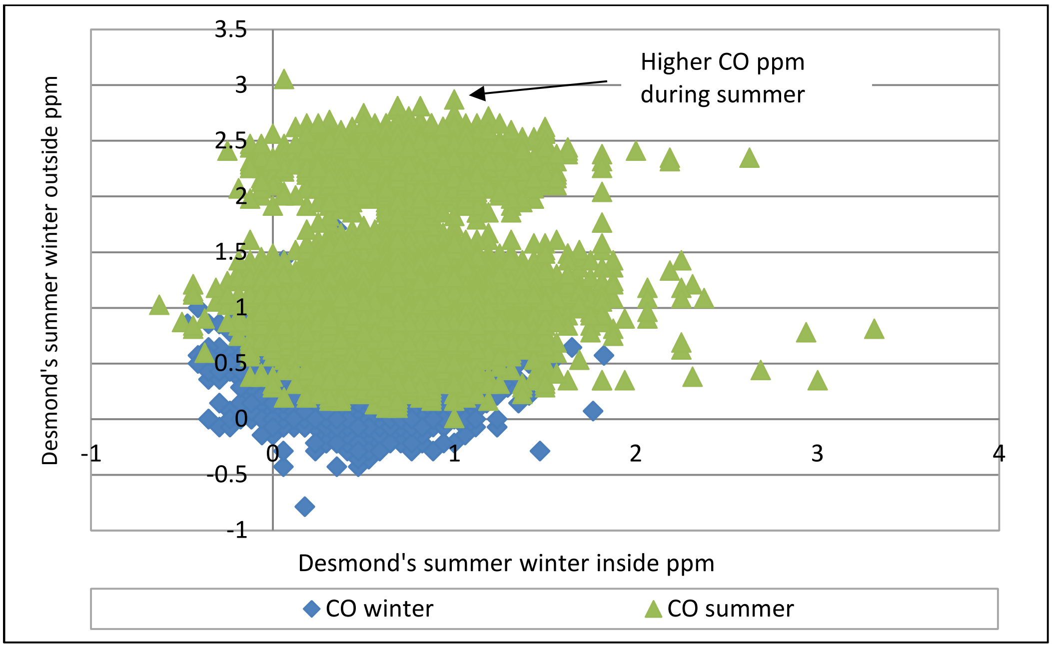


Figure 74 Kitchen and outdoor CO concentrations during summer and winter for an 'all electric' home.

[Note relative higher concentrations in kitchen and outdoors during the summer period].

4.2.4.2 Individual household air quality results over 14 days

The study period covered was 14 days both during the summer and winter months for Mary's house. The example household uses a gas fired combination boiler for space and water heating and a gas hob and gas oven for cooking. During the summer campaign when the study data was taken – it was observed that the household space heating was off but water heating kept on. During the winter the gas boiler was fully operational for both space and water heating.

The general layout of the house was shown earlier in Figure 71; the layout of the remaining studied homes are shown in 18 Appendix 8. The results of the air monitoring parameters for Mary's kitchen (indoor) and garden (outside) sensor unit are shown in Figure 75 and Figure 76. The results show CO, temperature and humidity peaks during indoor cooking events over the 14 days with the largest peak at 8,500 minutes into the monitoring. Outdoor observed features include – substantial humidity swings and several peaks associated with CO.

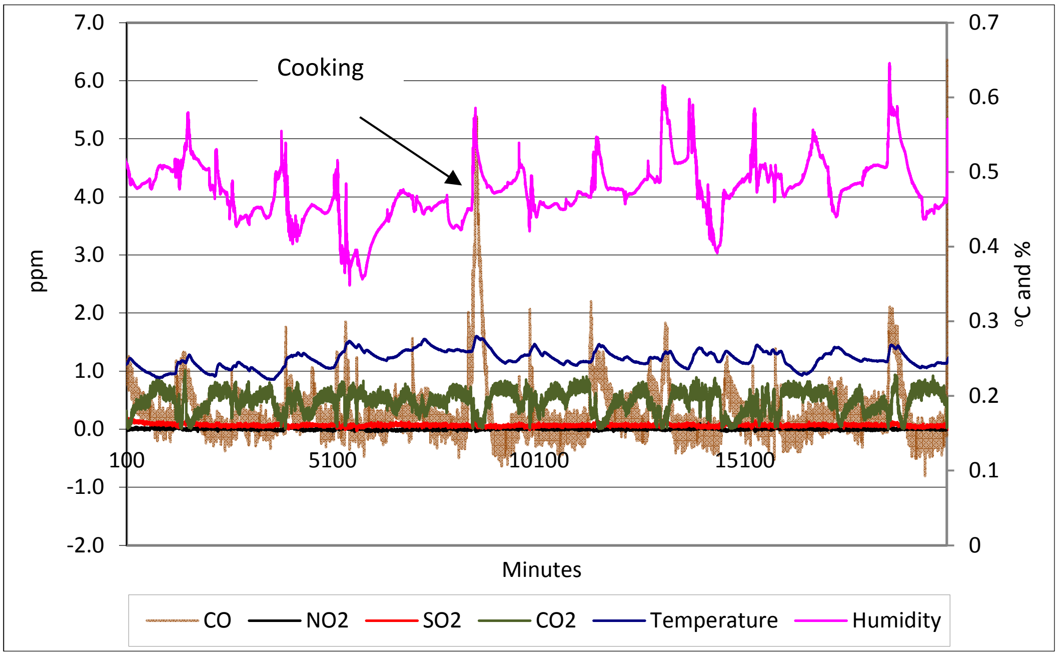


Figure 75 Kitchen emissions during 14 day summer monitoring period – Mary's house.

[Original CO, NO_2, SO_2 values can be taken directly from the left y-axis and CO_2 obtained by multiplying the values from the left y-axis by 1,000; temperature and humidity have been scaled to fit and original levels obtained by multiplying the values from the right y-axis by 10].

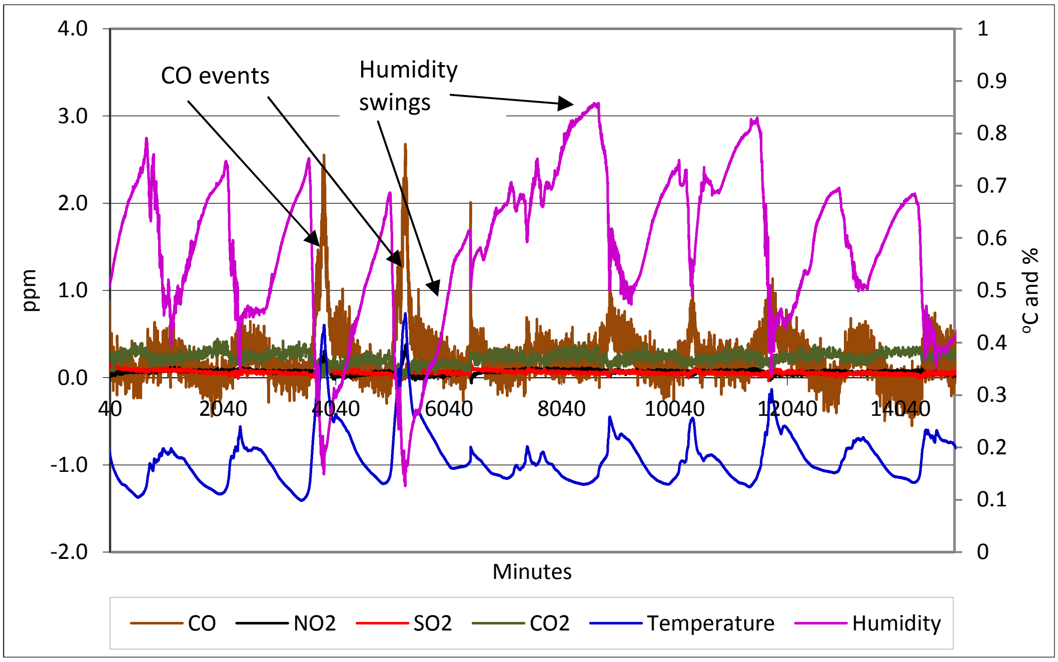


Figure 76 Outdoors emissions during 14 day summer monitoring period – Mary's house.

[Original CO, NO_2, SO_2 values can be taken directly from the left y-axis and CO_2 obtained by multiplying the values from the left y-axis by 1,000; temperature and humidity have been scaled to fit and original levels obtained by multiplying the values from the right y-axis by 10].

From the main data provided by each household; three notable events each were selected based on the peak measurements seen during the 14 day monitoring period. The peaks principally relate to CO emission and cooking events and generally cover -

breakfast, lunch or evening meal times. Specific events selected for further detailed analysis are shown in Table 20.

Table 20 Description of selected event data.

	Mary		**Madelief**		**Margaret**		**Desmond**	
Season Location	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Kitchen sensor: (date, time duration and minutes into monitoring period)	30/06/11 17:00- 20:00 1,244 04/17/11 17:00- 20:00 7,003 05/07/11 17:00- 20:00 8,443	09/02/21 16:00- 20:00 8,425 13/02/12 16:00- 20:00 14 185 15/02/12 16:00- 20:00 17,065	03/07/11 07:00- 11:00 5,013 05/07/11 09:00- 12:00 8,013 06/07/11 16:00- 20:00 9,873	29/11/11 08:00- 11:00 744 02/12/11 09:00- 12:00 5,124 04/12/12 12:00- 15:00 8,184	24/07/11 16:00- 20:00 2,664 25/07/11 16:00- 20:00 4,096 26/07/11 16:00- 20:00 5,532	24/03/12 16:00- 21:00 1,185 26/03/12 16:00- 20:00 4,065 27/03/12 16:00- 21:00 5,805	29/06/11 15:00- 20:00 1,066 04/07/11 16:00- 20:00 8,327 05/07/11 06:00- 10:00 9,167	02/12/11 05:00- 08:30 3,712 05/12/11 17:00- 20:00 7,508 06/12/11 16:00- 20:00 8,488
Outside sensor:	Date, times and starting points match those of the kitchen sensors above.							

[Kitchen and outside sensors showing date and time of samples and minutes into total monitoring period].

4.2.4.3 Individual household (indoor and outdoor) event results

The results of a typical summer kitchen cooking event in Mary's home are shown in Figure 77; the period covers the preparation of an evening dinner covering the start and finish of cooking and specifically at minute 1,300 and 1,460. Initially seen from the figures, are changes in CO, temperature and increasingly humidity. Only small changes are observed in the concentrations of NO_2 and SO_2. Carbon monoxide attains a maximum emission of 1.33 ppm from a room average of 0.09 ppm as would be expected with the use of a gas hob (as in this case). A small increase in temperature is observed during the cooking period with humidity changing measurably after initially experiencing steady state conditions; CO_2 concentrations range from (10 – 700 ppm).

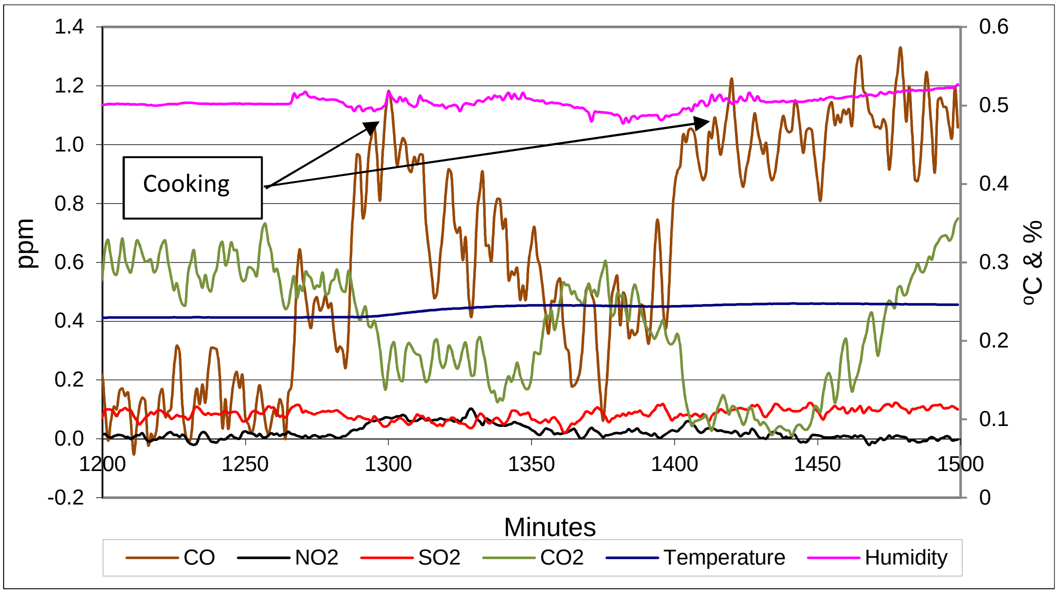


Figure 77 Kitchen emission and parameters for cooking event on 30/06/2011 – Mary's house.

[A summer cooking event using a gas oven and hob with gas fired space heating turned off. Original CO, NO_2, SO_2 values can be taken directly from the left y-axis and CO_2 obtained by multiplying the values from the left y-axis by 1,000; temperature and humidity have been scaled to fit and original levels obtained by multiplying the values from the right y-axis by 10].

Outdoor monitoring results for the same cooking event are reproduced in Figure 78. Again NO_2 and SO_2 are steady across the cooking event while humidity slowly increases from 46% to 57% across the event. The CO shows background swings with an average across the event of 0.18 ppm and peak at 0.45 ppm. The temperature shows a slow decline from 18.3 ^{o}C to 15.1 ^{o}C which ties in with the evening drawing to a close.

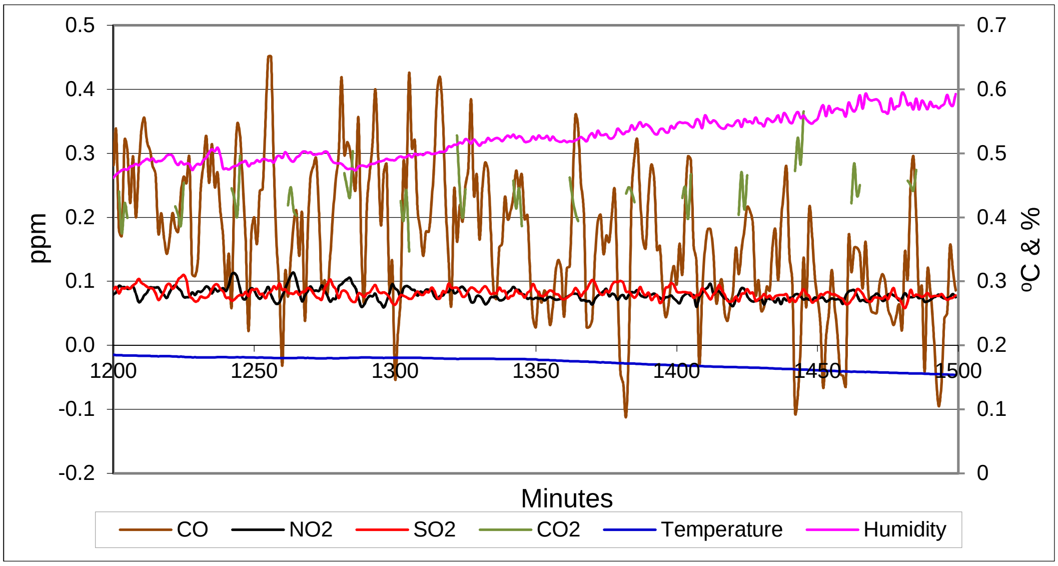


Figure 78 Outdoor emission and parameters for cooking event on 30/06/2011 – Mary's house.

[Original CO, NO_2, SO_2 values can be taken directly from the left y-axis and CO_2 obtained by multiplying the values from the left y-axis by 1,000; temperature and humidity have been scaled to fit and original levels obtained by multiplying the values from the right y-axis by 10. Note: partial CO_2 data shown as readings are only taken every 15 minutes for 4 minutes].

When similar cooking events are observed from an 'all electric' home the results suggest a range of similar activities; the kitchen (indoor) and external (outdoor) results are shown in Figure 79. The work shows a moderate change in CO levels over the cooking event resembling that seen from the outside sensor results. As also experienced for the 'all gas' system; NO_2 and SO_2 levels are relatively low at below 0.1 ppm with temperature and humidity levels showing little change.

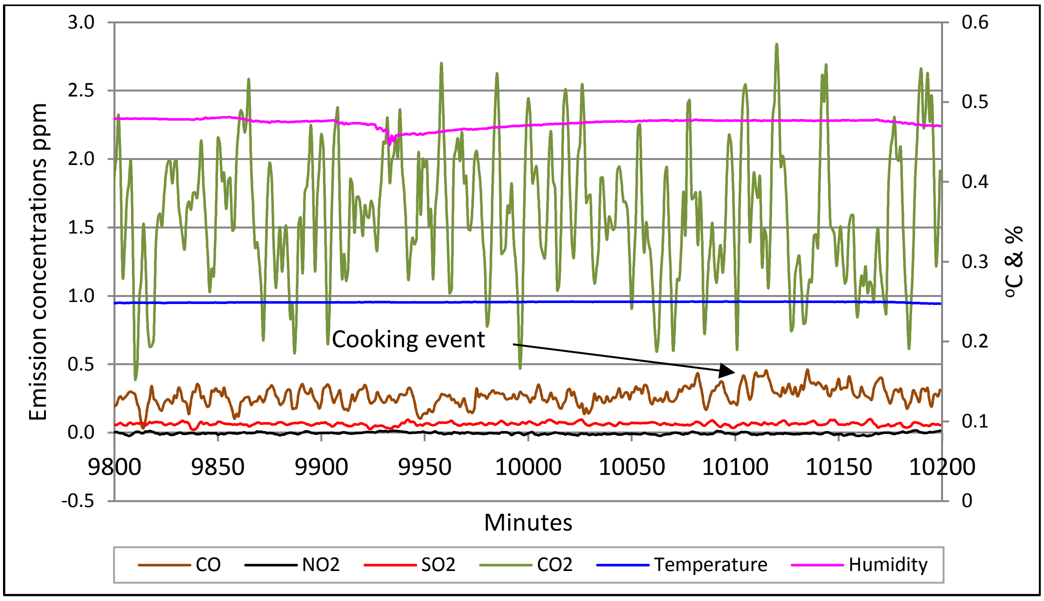


Figure 79 Kitchen emission and parameters for cooking event 06/07/11 - Madelief's house.

[A summer cooking event using an electric oven and hob with electric space heating turned off. Original CO, NO2, SO2 values can be taken directly from the left y-axis and CO2 obtained by multiplying the values from the left y-axis by 1,000; temperature and humidity have been scaled to fit and original levels obtained by multiplying the values from the right y-axis by 10].

Winter monitoring of an 'all gas' home event reveals higher levels of emissions as shown in Figure 80 with the CO peak at 12.9 ppm and CO_2 at 3,250 ppm.

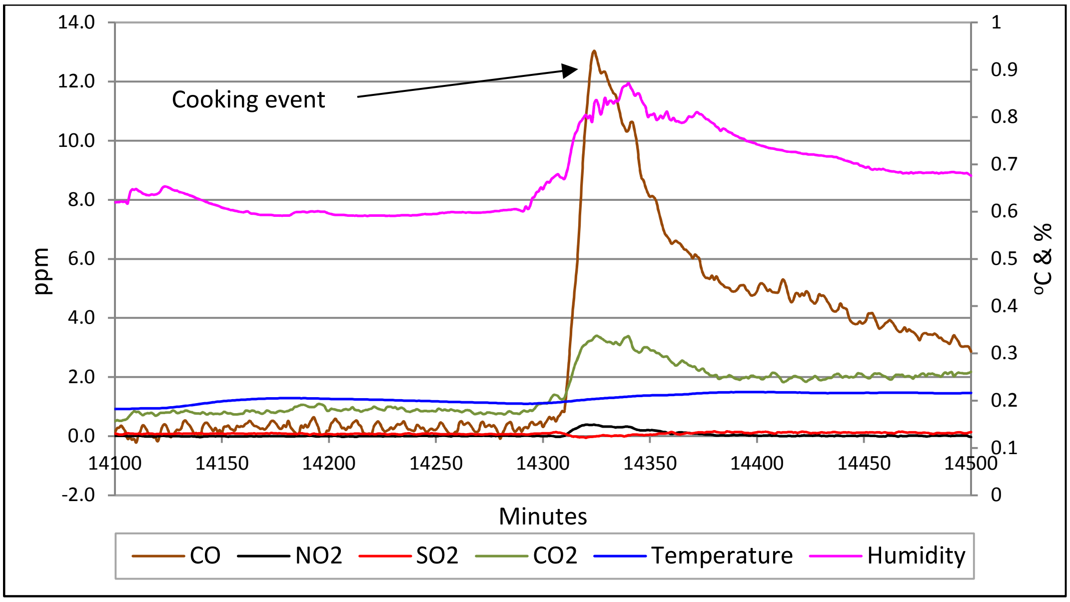


Figure 80 Kitchen emissions and parameters for a cooking event – Mary's house.

[Winter cooking event with gas oven and hob used; gas and gas space heating turned on. Original CO, NO_2, SO_2 values can be taken directly from the left y-axis and CO_2 obtained by multiplying the values from the left y-axis by 1000; temperature and humidity have been scaled to fit and original levels obtained by multiplying the values from the right y-axis by 10].

4.2.4.4 Individual household indoor cooking event results

The summary of the maximum, minimum and mean recordings for each of the homes across the two monitoring seasons are shown in Table 21. Notable data is highlighted for each home by comparing and contrasting with the others.

Table 21 Measured levels of indoor CO, CO_2, NO_2, SO_2, temperature and humidity for the case study homes over the 14 day monitoring period.

Study home:		Mary		Madelief		Margaret		Desmond	
Element:		Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
CO (mg /m^3)	Max	**15.30**	6.81	2.15	0.97	3.03	**9.50**	2.09	3.44
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mean	**1.35**	0.32	0.56	0.26	**0.69**	0.15	0.53	0.45
CO_2 (mg /m^3)	Max	**8,194.30**	2,107.03	1,191.88	**12,198.17**	3,096.67	2,721.91	2,677.50	1,210.95
	Min	0.57	0.00	0.00	1.68	5.08	0.00	0.57	0.00
	Mean	1,211.01	867.16	247.00	**3,330.03**	**1,932.62**	1,024.56	482.85	360.45
NO_2 (µg /m^3)	Max	**754.90**	371.66	252.74	142.14	215.69	**776.76**	387.14	267.34
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mean	26.84	6.77	20.87	4.60	3.88	13.27	21.93	8.74
SO_2 (µg /m^3)	Max	**610.07**	**610.73**	337.71	596.04	**678.76**	**600.70**	591.83	396.68
	Min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mean	165.64	**176.85**	35.63	166.80	160.48	**189.26**	116.68	50.72
Temperature (^{o}C)	Max	24.98	**27.98**	22.22	25.58	26.23	26.39	19.25	25.90
	Min	15.27	22.21	20.20	22.32	17.14	19.80	**12.88**	19.10
	Mean	19.33	**24.95**	21.07	23.80	22.36	22.92	**15.48**	22.09
Humidity (%)	Max	**87.89**	64.55	63.93	52.76	52.84	76.42	69.93	66.85
	Min	36.53	34.85	46.09	40.04	**34.82**	47.78	49.82	41.63
	Mean	55.63	47.55	53.75	46.80	41.97	57.94	**59.10**	52.59

The following analysis is determined by comparing the results as shown in Table 21 over various time periods with those of the reference guidelines (HMGOV, 2010; WHO, 2010; ASHRAE, 2010):

- Carbon monoxide – peak levels are found in Mary's and Margaret's homes at 15.3 mg/m^3 and 9.50 mg/m^3 respectively. Considering the mean levels of 1.35 and 0.15 over a 14 day period for the same homes this shows the peak levels reflect specific events – in this case cooking events. Mean averages do not exceed guideline limits although peak concentrations could in the case of Mary and Margaret's homes.
- Carbon dioxide – Madelief's and Mary's homes show peak levels at 12,198 mg/m^3 and 8,194 mg/m^3 respectively. Again mean levels are substantially lower at 3,330 mg/m^3 and 1,211 mg/m^3 respectively which may offer a grade of concern however - Madelief's result reflects a reluctance to open windows for ventilation rather relying on the time controlled extractor fan.

- Nitrogen dioxide – peak levels are relatively high with Mary's house (winter) at 754.9 µg/m^3 and Margaret's house (summer) at 776.8 µg/m^3.
- Sulphur dioxide – gas fuelled homes (Mary and Margaret) both exceed 600 µg/m^3 peaks and all homes could potentially exceed the 10 minute mean test at 500 µg/m^3 and 24 hour mean at 20 µg/m^3.
- Temperature and humidity – temperatures are moderately consistent across the studied homes with only Desmond's showing lower kitchen maximum, minimum and mean temperatures during the winter period. Mean humidity levels are again consistent across the studied homes with a peak of 87.9 % found in Mary's home during the winter study.

Further investigation and comparison of both peak and mean concentrations from the study homes is conducted to determine if guideline limits had been exceeded and to which house type these apply – summary results are shown in Table 22 and the analysis provides the following findings:

- Carbon monoxide – none of the homes exceed the guideline limits shown either across the 1 hour, 8 hour or 24 hour timeframes. However, it is observed that the gas fuelled homes have substantially higher levels of peak CO concentrations while mean levels are less clear over the two types (gas and electric).
- Carbon dioxide – no clear pattern emerges.
- Nitrogen dioxide – annual average levels are not measured here – however, the 1 hour average is exceeded by Mary's house and is also close to the limit for Margaret's home - the two electric homes have relatively lower concentrations.
- Sulphur dioxide – all homes have lower concentrations than the 10 minute mean guideline although the 24 hour test reveals substantially higher concentrations for both gas fuelled homes.

Table 22 Comparison of indoor guideline concentrations with the studied home results based on home emission events.

[Where n/a is shown this indicates results below guideline limits].

Gas	Guideline concentrations	Mary	Madelief	Margaret	Desmond
	Date and time:	13/02/2012 @ 18:19	n/a	31/07/2011 @ 11:43	n/a
CO	15 minute – 100 mg /m^3 1 hour – 35 mg /m^3 8 hour – 10 mg /m^3 24 hours – 7 mg /m^3	n/a 8.021 3.006 1.362	n/a	n/a 0.799 0.867 0.225	n/a
	Date and time:	09/02/2012 @ 21:44	07/07/2011 @ 17:58	n/a	n/a
CO_2	>5,000 ppm	8,194	12,197	n/a	n/a
	Date and time:	13/02/2012 @ 18:17	n/a	31/07/2011 @ 11:42	n/a
NO_2	1 hour average – 200 µg /m^3 Annual average – 40 µg /m^3	349.68 n/a	n/a	171.23 n/a	n/a
	Date and time:	06/02/2012 @ 20:27	n/a	25/03/12 @ 11:21	n/a
SO_2	10 minute mean 500 µg /m^3 24 hour mean 20 µg /m^3	448.22 214.70	n/a	191.18 214.90	n/a

4.2.5 Principal component analysis

Principal component analysis (PCA) is conducted on the results from each home; covering the summer and winter monitoring and for the range of cooking events described previously in Table 20. Data obtained from the sensor units is first adjusted using calibration coefficients calculated from pre and post monitoring calibration for each of the units. Data are normalised, specific cooking events identified and the associated values entered into the community analysis programme (Conservation, 2007) where detailed analysis takes place. The homes are coded with the names: Madelief, Margaret, Mary and Desmond. A principal component analysis is performed using PCA co-variance – first, considering each season and the corresponding inside and outside values, secondly, indoor values for both the summer and winter seasons. The results of the PCAs are now discussed.

4.2.5.1 Summer kitchen and outdoor results

The indoor emission events from each case study home for summer monitoring are combined within the PCA to determine variance and variability. Immediately it is seen that most of the vectors are tightly grouped in the centre of the plot Figure 81, however there are a number of strong vectors with associated event data points. For this analysis, the first 3 dimensions resume 90% of total variance of the dataset – see 18 Appendix 8.

For comparison, Figure 82 shows the plot when PCA is performed on 'all electric' homes during the summer monitoring period. Distinctive within the plot is a central clustering with little variation of kitchen data from both homes but a strong correlation with CO_2 on Desmond's outside data. Further, Figure 83 indicates the plot of 'all gas' homes again during the summer monitoring period. The vector suggests that Mary's indoor emissions have a close variability with CO during the cooking events and Margaret's indoor emissions reflect a less strong but evident variability with the same.

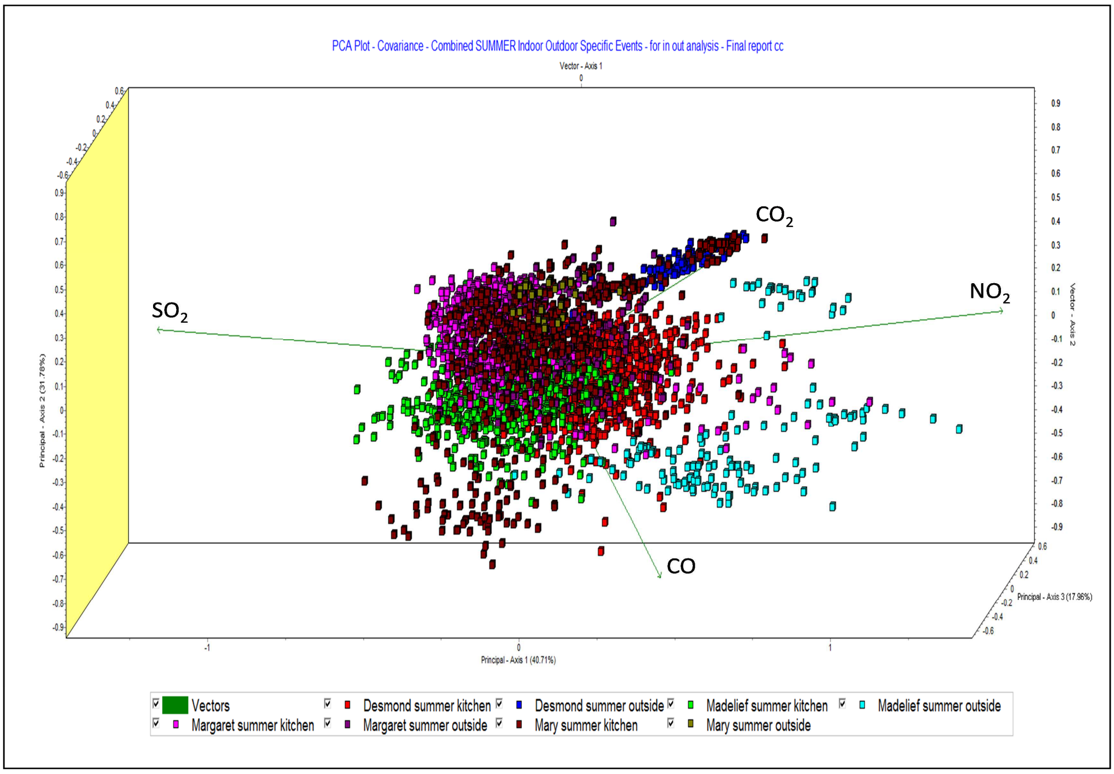


Figure 81 Principal component analysis – 'all homes' data during summer emission monitoring.

[Emissions are grouped to show the variance and variability of each cooking event when considering both kitchen and outdoor concentrations with Principal axis 1, 40.7%; 2, 31.8%; and 3, 18.0%].

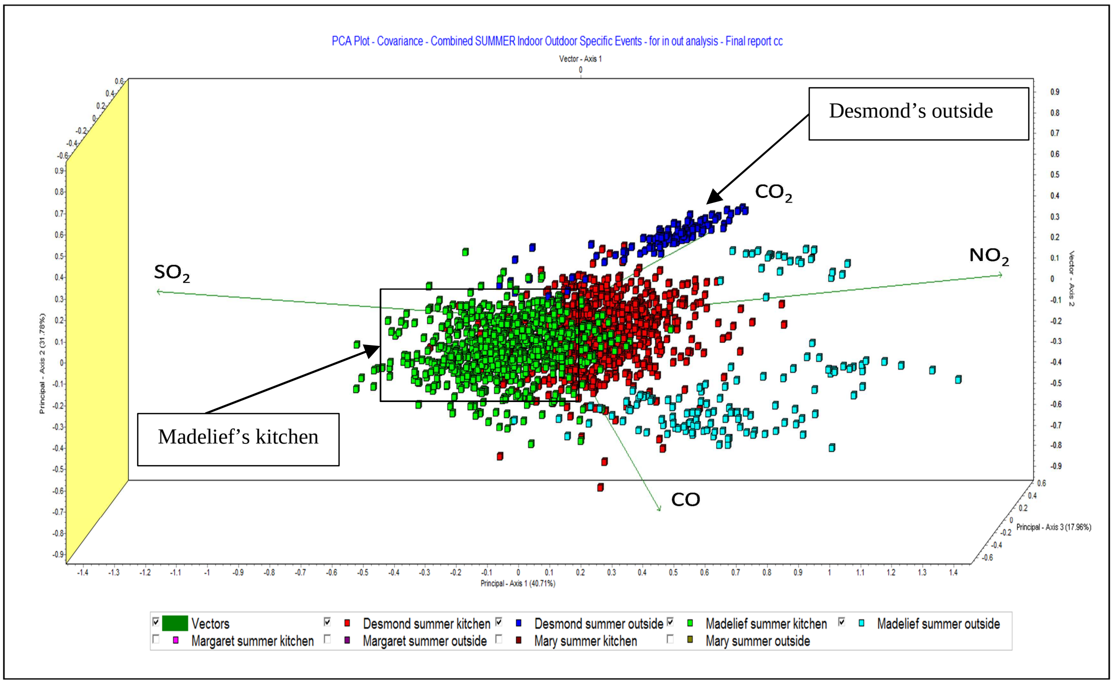


Figure 82 Principal component analysis - 'all electric' only homes data during summer emission monitoring.

[Emissions are grouped to show the variance and variability of each cooking event when considering both kitchen and outdoor concentrations with Principal axis 1, 40.7%; 2, 31.8%; and 3, 18.0%].

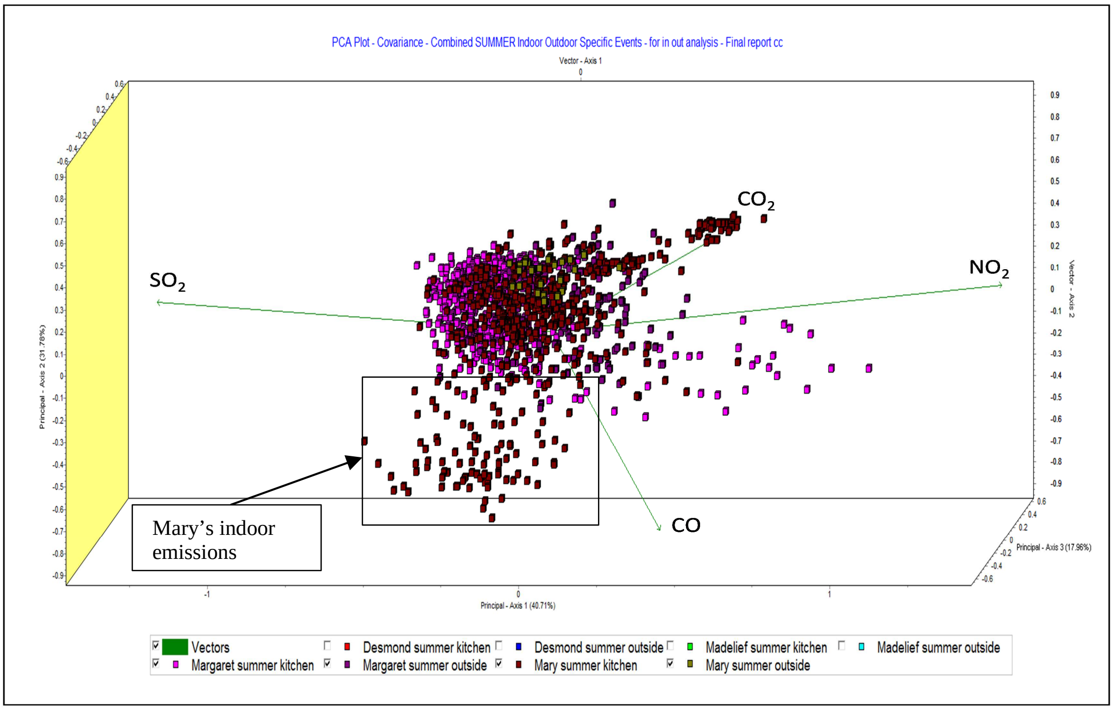


Figure 83 Principal component analysis - 'all gas' only homes data during summer emission monitoring.

[Emissions are grouped to show the variance and variability of each cooking event when considering both kitchen and outdoor concentrations with Principal axis 1, 40.7%; 2, 31.8%; and 3, 18.0%.]

4.2.5.2 Winter kitchen and outdoor results

PCA on the winter data for all homes presents the plot shown in Figure 84 and observation shows that key components can be represented again through 3 principal components – see 18 Appendix 8. Analysis of ‘all electric’ home plot shows clustering generally in the centre of the plot with little variation although the Eigenvectors show a tight pair (NO_2, CO). When the ‘all gas’ homes are considered only as in Figure 85, there is close correlation between CO and NO_2 for Mary’s and Margaret’s winter kitchen datasets.

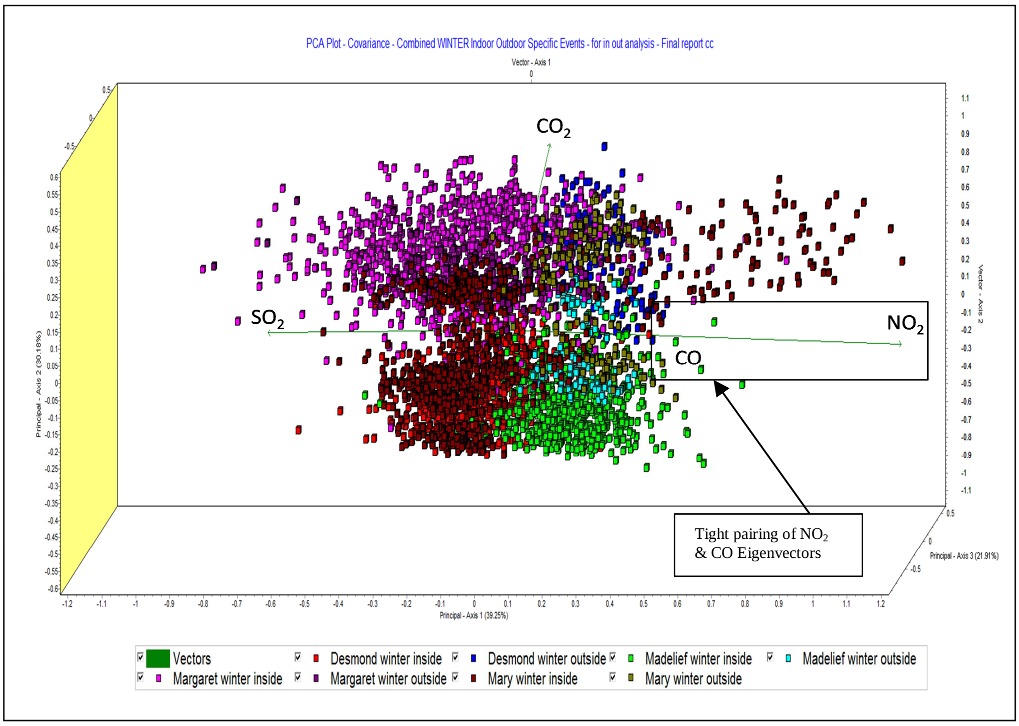


Figure 84 Principal component analysis – all study homes data during winter emission monitoring.

[Emissions are grouped to show the variance and variability of each cooking event when considering both indoor and outdoor concentrations with Principal axis 1, 39.2%; 2, 30.2%; and 3, 21.9%].

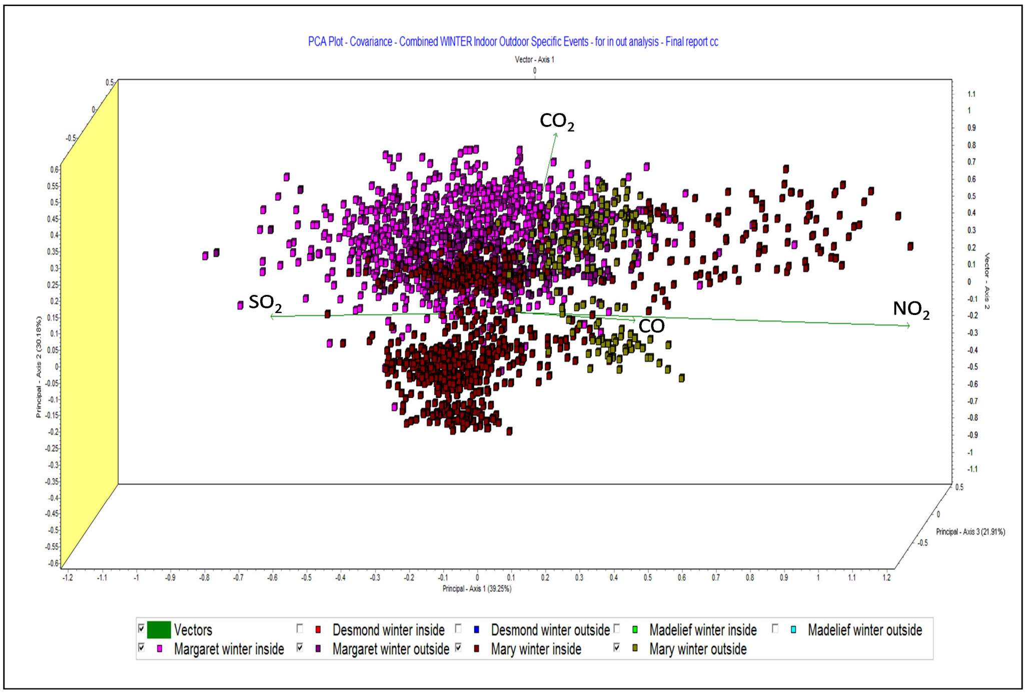


Figure 85 Principal component analysis - ‘all gas’ only homes data during winter emission monitoring.

[Emissions grouped to show the variance and variability of each cooking event when considering both kitchen and outdoor concentrations with Principal axis 1, 39.2%; 2, 30.2%; and 3, 21.9%].

4.2.5.3 Summer and winter kitchen results

An examination of the PCA plots obtained from the summer and winter indoor results shows that the first 3 dimensions are the most meaningful resume 90% of the total variance of the dataset– see 18 Appendix 8. Further examination into the ‘all electric’ homes and ‘all gas’ homes detailed in Figure 87 reveals a clustering of concentrations around the centre of the axis for ‘all electric’ homes showing little variation while for the ‘all gas’ homes there is the development of clusters within the NO_2 and CO showing considerable variation especially relating to Margaret’s summer and Mary’s winter dataset.

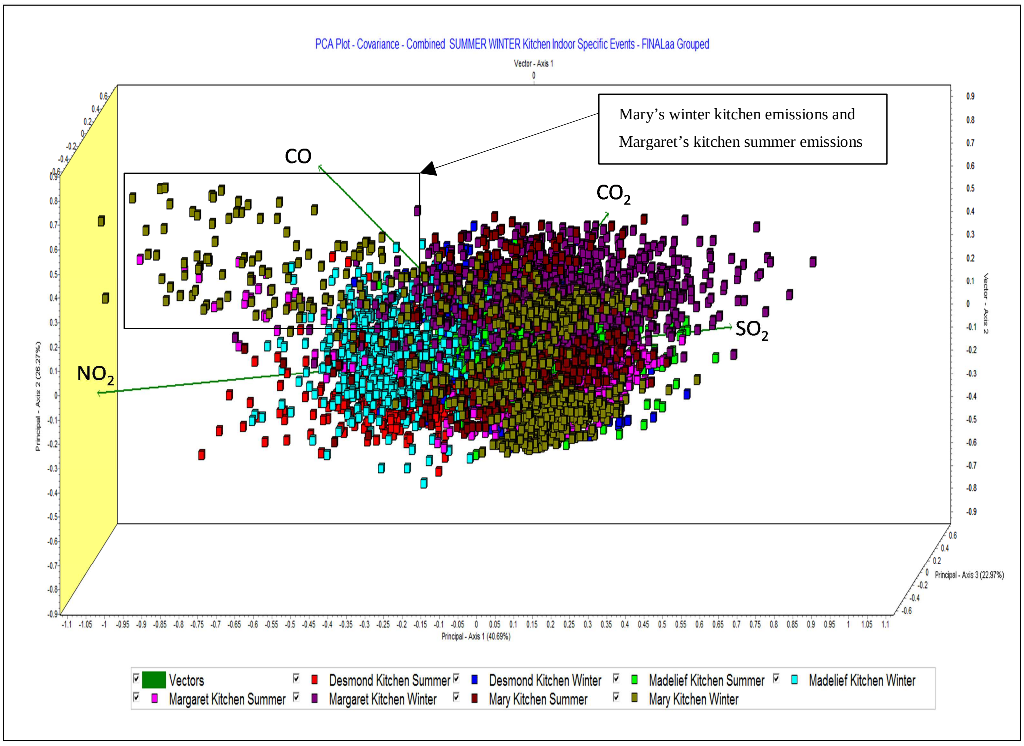


Figure 86 Principal component analysis – all homes data during summer and winter emission monitoring.

[Grouped to show variance and variability of each cooking event when considering kitchen only concentrations with Principal axis 1, 40.7%; 2, 26.3%; and 3, 23.0%].

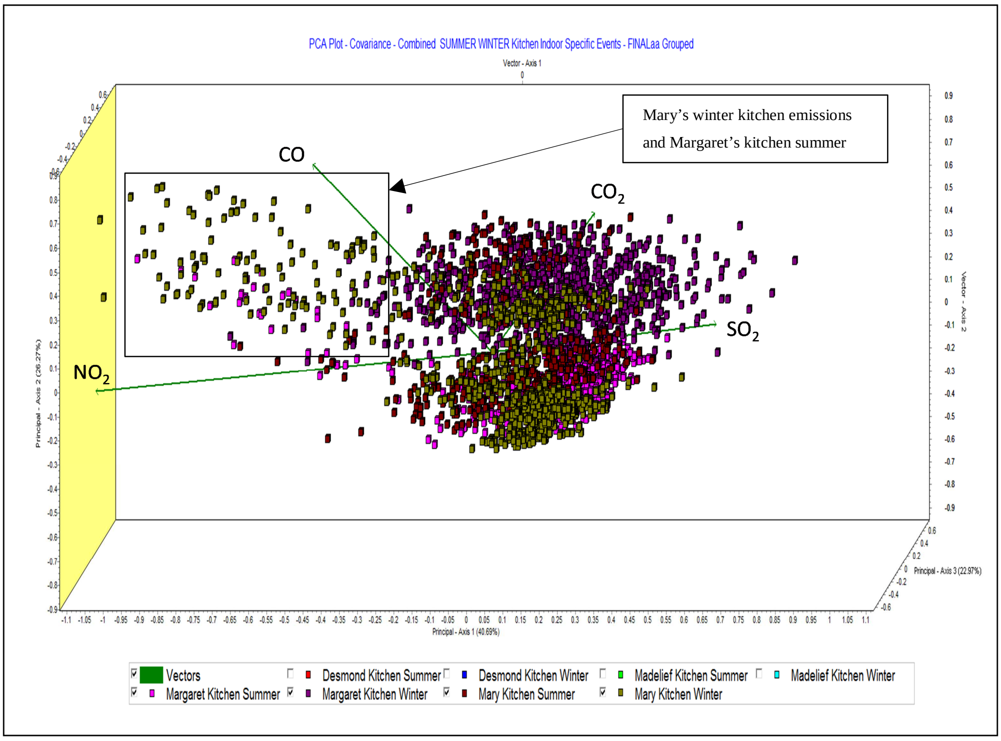


Figure 87 Principal component analysis - 'all gas' only homes data during summer and winter emission monitoring.

[Emissions grouped to show variance and variability of each cooking event when considering only indoor concentrations with Principal axis 1, 40.7%; 2, 26.3%; and 3, 23.0%].

4.2.6 Discussion of the kitchen emission monitoring results

Comparing the indoor air monitoring results as seen from the two ‘all gas’ fuelled houses studied (Mary’s and Margaret's) shows that there are similarities in terms of the concentration changes in CO, CO_2 and NO_2. A greater increase in CO to the indoor environment is evident during cooking events especially within the ‘all gas’ homes and this appears to match the households use of the gas oven or hob. Moreover, winter results from all homes indicate high indoor concentrations as would be expected with lower ventilation rates – this is particularly true for CO. Further PCA shows variation in CO and NO_2 within the ‘all gas’ homes, again related to the use of natural gas during cooking. Elsewhere, temperature and humidity changes are moderately consistent across all homes and the same is true for SO_2 concentrations.

Direct implications for the use of any particular domestic heat providing system is important especially considering the indoor environment and emissions studied in this section. Indoor air quality within urban or city housing are an expression of many varying factors and as demonstrated, the role of cooking and cooking events in air emissions is fundamental.

Observed cooking emissions suggest acceptable levels of CO within the homes but challenges with NO_2 and SO_2 in ‘all gas’ dwellings. Based on the initial assumption that gas boilers or similar appliances have ‘effective flues’ and electric heating appliance produce negligible observed contributions - key emissions then predominately arise from cooking. The use of certain types of extractor fans and overall ventilation during cooking can facilitate indoor and outdoor air quality changes (Abdullahi et al., 2013; Ashmore and Dimitroulopoulou, 2009) however as the study has shown, effectiveness depends on the correct use and timing by householders.

Despite extraction and ventilation; ‘all gas’ homes could be experiencing 47% higher CO, 9% higher NO_2 and 39% higher SO_2 during any winter season when compared to ‘all electric’ homes at the point of emission recording. Average emission levels observed across the ‘all gas’ and ‘all electric’ homes for CO, CO_2, SO_2 and NO_2 are taken as indicators for use in the multi-criteria decision analysis (MCDA) – Chapter 7.

4.2.7 Summary

- The air monitoring units have shown that it is possible to measure and record the air quality parameters of households over a 14 day period. The data recorded have been analysed using a range of tools. Changes in emission levels and subsequent trends have been observed from the data; with the more obvious changes occurring during cooking events - for example, increasing or changing levels of CO and CO_2 during cooking events using gas and electric in households. Other observed emission changes have been related back to householder activities during monitoring and confirmed by specific entries in occupants' diaries.
- The results provide evidence of differences in emission levels between those homes using gas for cooking and those using electricity. The changes and differences are evident across a number of cooking events conducted during the 14 day period and demonstrate notable higher emission levels for gas than for electric cooking systems.
- Overall kitchen emission levels are also increased during winter when compared to the summer and are reflected at both peak and mean levels.
- When considering guideline limits – 'all gas' homes have a tendency to come close to or exceed both the NO_2 and SO_2 limits and produce substantially higher levels of peak CO concentrations than 'all electric' during cooking events. Mean CO levels are less clear over the two types (gas and electric).
- The 24 hour test reveals substantially higher concentrations of SO_2 for both gas fuelled homes. For NO_2 - the 1 hour average test is close to or exceeds the limit by the 'all gas' homes - the two electric homes have relatively lower concentrations.
- The work conducted on cooking event data using principal component analysis suggests that much of the variability in emission composition can be expressed in 3 dimensions. The vectors suggest that 'all gas' kitchens are strongly correlated with CO and NO_2. Overall, indoor and specifically kitchen emissions are a combination of the sources and factors described previously in Figure 70.

However, the contribution of 'heat providing systems' to the total during cooking events could be significant especially for gas fuelled systems.

The two previous sections have identified the environmental sustainability from the perspectives of life cycle impacts and direct impacts. The following Chapter evaluates the economic sustainability of the heat-providing systems.

5. Evaluation of economic sustainability using Life Cycle Costing (LCC)

The evaluation of economic sustainability of the systems providing space, water and cooking heat has been conducted using life cycle costing (LCC), following the methodology described in Chapter 3. The results obtained from the LCC are used to estimate and compare the economic sustainability of eight heat-providing systems.

5.1 Goal and scope definition

The goal of the LCC study is to:

- estimate and compare the economic costs of the eight heat-providing systems studied here over a 40 year operational period;
- identify the activities in the life cycle that contribute the most to the cost impacts; and
- identify cost improvements opportunities for urban housing heating systems.

The scope of the study is from 'cradle to grave', and the approach considers the following life cycle stages: purchase and installation, system operation, maintenance and disposal (see Figure 88).

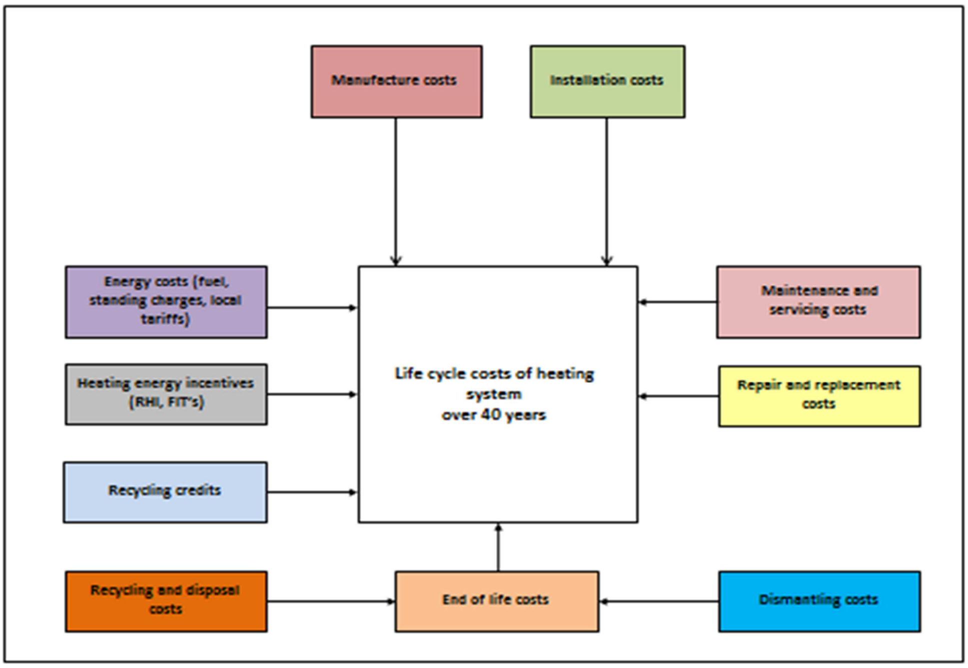


Figure 88 System boundaries and costs included in life cycle costing for the eight heating systems.

5.1.1 Functional unit

The functional unit is defined as the ‘operation of a heating system in one apartment block over a 40 year period’. The heating systems are the same as described in the LCA Chapter 4.

5.1.2 Assumption and limitations

The assumptions are the same as those made in the LCA study. Further assumptions related to the costs are as follows:

- Costs for equipment and/or components include installation costs (labour and materials).
- Construction costs include the replacement of equipment at its end of life and the repair of component parts during its operation.
- Both the current and costs of the systems over time are estimated. Net present value is used for the latter, assuming discount rates of 5% and 10%, respectively (Churcher, 2008).
- Engineering, planning and projects management costs are based on capital cost invested and range from 6% for simple systems such as the electric panel to 12% for the more complicated and demanding systems for example the district heating and CHP systems.
- It is assumed that VAT and preliminaries do not change in real terms during the 40 year period.
- The eight systems considered do not generate revenues directly except end of life scrap values and the systems have been credited for this where appropriate.
- Disposal of the system components follows current scrap prices and dismantling costs.
- Where the unit cost of electricity generation to householders is higher than the cost of production (as in the CHP system), this is reflected in the calculations.
- Assets older than five years of age are not considered (Churcher, 2008) to have a residual value.

Life cycle cost data have been collected from a number of sources including:

- Spon’s Mechanical and Electric Services Price Books (Spon's, 2010b);
- Spon’s Civil Engineering and Highway Works Price Books (Spon's, 2010a);
- Rules of thumb – Guidelines for building services (5^{th} edition) (BSRIA, 2011);
- Expert consultations; and
- Own experience and estimates.

The life cycle costing stages are now described based on the material and energy flows for each of the eight studied systems and outlined earlier in the LCA chapter, section 4.2.

Manufacture: this stage includes - the manufacture and assembly of the heating system components in the factory from the raw and semi processed materials and components. Cost indicators are taken as the price for the heating system components either from the manufacture directly or through their sales agents. Table 23 provides details of the costs of major technologies in each system; also included are planning allowances based on the costs of project planning and management and transport costs associated with moving the components and equipment ready for installation.

Installation: considered in this section are the installation of the system within the building and apartments and the commissioning stage of each system. Summary costs associated with this stage are shown in Table 24.

Operation: this stage includes: the energy (electricity or gas) consumed during the operation (heating, cooking, water pumping etc.) of each system over 40 years. Fuel unit prices and the average calculated unit price for gas and electricity are estimated from 2012-2013 energy prices (see Table 25) and are assumed as being consistent over the 40 year period. Currently, incentives are available from the government for renewable energy based systems and include the renewable heat incentive (DECC, 2013c) and feed-in tariffs (DECC, 2011b) - incentives included in the assessment are shown in Table 26.

Maintenance: this stage also considers any ongoing maintenance, servicing and repairs of the system – the estimates are shown in Table 24.

End of life: dismantling and disposal - the end of life stage includes: the decommissioning and removal of some or all of the heating system components and materials during and at the end of the 40 year period. The weight of materials used during manufacture and installation and any replacement during the 40 years have been determined (see Chapter 4) and scrap sale costs calculated based on current values.

Table 23 Estimated (capital) costs of the heating system technologies.

Technology / Cost (£)	Units	Electric panel	Electric storage	ASHP	Gas boiler	Combined gas and electric	District heating	CHP district heating	Solar thermal and gas
Electric panels heaters	panel	£175 per kW (Poyry et al., 2009)				£175 per kW (Poyry et al., 2009)			
Electric storage heaters	heater		£175 per kW (Poyry et al., 2009)						
Air source heat pump	pump			£600 per kW (Poyry et al., 2009)					
Gas boiler	boiler				£2 500[1] (Poyry et al., 2009), £1,825 (Spon's, 2012)				£1,062 (Spon's, 2012)
Centralised gas boilers[2]	boiler					£60 per kWth[3] (Poyry et al., 2009), £5 503 (Spon's, 2012)	£60 per kWth (Poyry et al., 2009), £5 503 (Spon's, 2012)		
Combined heat and power unit[4]	unit							£864 per kWe[5] (Poyry et al., 2009), £600-1,200/kWe (BSRIA, 2011), £104,294[6] (Spon's, 2012)	
Solar thermal panel	panel								£1,429 per kW (Poyry et al., 2009)
Immersion heaters and water storage cylinders	unit	£843 (Spon's, 2012)	£843 (Spon's, 2012)	£843 (Spon's, 2012)			£843 (Spon's, 2012)	£843 (Spon's, 2012)	£843 (Spon's, 2012)
Energy centre	unit						£450 per m^2 (BioRegional, 2012)	£450 per m^2 (BioRegional, 2012)	
District heating infrastructure	dwelling						Infrastructure £1,000, Branch £1,500, Heat station/meter £2,300 (Poyry et al., 2009)	Infrastructure £1,000, Branch £1,500, Heat station/meter £2,300 (Poyry et al., 2009), gas CHP and gas back-up £753,172 (BioRegional, 2012),	

[1] Dominated by installation costs, [2] Centralised gas boilers installed (£40/kW), [3] Includes plant and installation but not building, [4] CHP unit installed (£1,500/kW_e) generating (TV Energy, 2010), [5] Includes: plant, installation, and associated energy centre, [6] Based on 82kWe and 132kWth output

Table 24 Installation, establishment costs and details for the heating systems.

System	Units	Electric panel	Electric storage	ASHP	Gas boiler	Combined gas and electric	District heating	CHP	Solar thermal + gas
Planning and management costs[7]	%	6	6	10	10	10	12	12	11
Installation costs[8]	%	3	5	9	8	8	15	15	9
Operation and maintenance costs[9]	£/kW and £/kWth (district heating)	£17 per kW (Poyry et al., 2009)	£17 per kW (Poyry et al., 2009)	£9 per kW (Poyry et al., 2009)	£200 per year. (Poyry et al., 2009)		£3 per kWth year. (Poyry et al., 2009)	0.025[10] £80 per kW yr. (Poyry et al., 2009)	£4 per kW (Poyry et al., 2009)
Operation and administration costs (maintenance and metering)[11]	Gas % Elect % Heat %	- 1 -	- 1.5 -	- 1 -	2 1 -	2 1 -	2 1 3	2 1 3	2 1 1
Energy service company establishment[12]	£						50,000 (Poyry et al., 2009)	50,000 (Poyry et al., 2009)	

[7] The planning, management and engineering costs associated with the project are taken as 6 - 12 % of the overall capital cost of the project depending on system type.
[8] Based on rules of thumb (BSRIA, 2011) and system type.
[9] References shown are taken as guide only.
[10] Operation and maintenance costs for CHP unit only taken as (£0.025/kWh_e) (TV Energy, 2010).
[11] Includes the cost of meter provision and reading.
[12] Energy service companies are required to operate and manage specific systems but for the district heating and CHP heating system these may require establishing.

Table 25 Cost of energy supply to apartment blocks.

	Electricity (unit charge, pence/kWh)	Electricity (standing charge; £/year)	Natural gas (unit charge; pence/kWh)	Natural gas (standing charge, £)	Heat (from distribution system, pence/kWh)[13]	Heat district heating (standing charge, £)	Heat (from solar thermal system; pence/kWh)	Heat solar thermal (standing charge, £)
Standard	13.1	73	4.09	73		73		
Off-peak (day)	14.7	73						
Off-peak (night)	7.0	-						
Commercial	10.6	82.31	2.8	2,306	2.8	-	4.1	50
CHP[14]	13.1							

[13]Flat rate for heat supply set at (£0.04 /kWh for domestic customers) plus £150 per annum equivalent to individual annual gas boiler servicing (TV Energy, 2010), central plant natural gas fuel costs taken as (£0.025 /kWh), elsewhere, (DECC, 2012) provided a tariff of (£0.0464 /kWh) based on the commercial heat cost model i.e. comparing district heating costing with the equivalent gas boiler costing.
[14]Sale of electricity generated by CHP unit to householders through private network.

Table 26 Financial incentives available for the studied systems.

System Incentive (£ per kWh)	Units	ASHP[15]	District heating	CHP	Solar thermal and gas[16]
Renewable heat incentive (DECC, 2013c)	kWh thermal	0.0250	n/a	n/a	0.10
Feed-in tariff (DECC, 2011b)	kWh electric	n/a	n/a	0.1312	n/a

[15]Consultation rate as off May 2013.
[16]Up to 200 kW.

5.2 Life cycle costs of different heating systems

The following sections present and discuss the life cycle costs estimated for each system; they are compared in Section 5.3.

5.2.1 Electric panel system

The electric panel system uses only electricity for its heating and cooking and this involves a shared energy supply system with the household lighting and appliances. The total life cycle costs of the electric panel system are £3,001,811 assuming a 0% discount rate – Table 27. At 5% and 10% discount rates, the NPV are -£1,369,056 and -£847,028, respectively. However, with the electric panel system no direct commercial return is received as the system does not rely on the local generation of energy.

The specific life cycle costs associated with construction, installation, operational energy, dismantling, disposal and maintenance are given in Figure 89 and include estimates at 5% and 10% discount rates. The operational energy used by the panel system over the 40 years contributed the largest costs at 79% of the life cycle costs at 0% discount rate. The second largest contributor was the construction and replacement costs at a moderate 18% of life cycle costs - these include the electric panels', electric wiring, and hot water storage cylinders. Replacement and repair costs (included in the construction costs) over the 40 years are also moderate equating to approximately half the initial construction costs £228,100 (at 0% discounting).

The panel system has maintenance costs of £82,473 which are low because servicing requirements are infrequent. Installation costs are also relatively minor at £15,209 or 0.5% of overall cost using 0% discounting; this reflects the ease of installation as well as the sharing of the common energy supply system within the block and apartments. Finally, decommissioning costs and material disposal contribute the remaining £9,426.

Figure 90 shows the breakdown of costs by five-year intervals and the cumulative costs over 40 years. Larger expenditure is made during the years 6-10, 16-20, 21-25 and 26-30 when electric panels and immersion heaters are expected to be replaced.

Overall, the capital and installation costs are estimated at £196,391 or £56 per m^2 - this compares well to Poyry et al. (2009) and Spon's (2010b) who found that electric panel and immersion heating costs for a similar sized apartment block is approximately

£150,722 or £40 per m^2. The difference lies in the use of improved insulated cylinders and the inclusion of project planning and management costs in the current study.

Table 27 Life cycle cost inventory data for the electric panel system.

Cost type	Item	Cost over 40 years £ [NPV @ 0%]	Cost over 40 years £ [NPV @ 5%]	Cost over 40 years £ [NPV @ 10%]
Construction	Electric panels	176,500	93,717	64,706
	Common electric system wiring	69,300	42,667	36,636
	In-house wiring	99,200	61,076	52,443
	Immersion heaters	14,880	8,267	5,920
	Hot water cylinders	103,177	66,823	56,350
	Other: materials and equipment*	43,896	21,631	13,730
	Other: project planning and management	30,417	17,651	13,787
Installation		15,209	8,825	6,894
Operational energy	Electricity supplied	2,357,333	1,011,242	576,312
Dismantling & disposal		9,426	5,171	3,883
Maintenance	Including operation and administration	82,473	31,986	16,367
	Total life cycle cost:	3,001,811	1,369,056	847,028

*[Valve and electronics replacement].

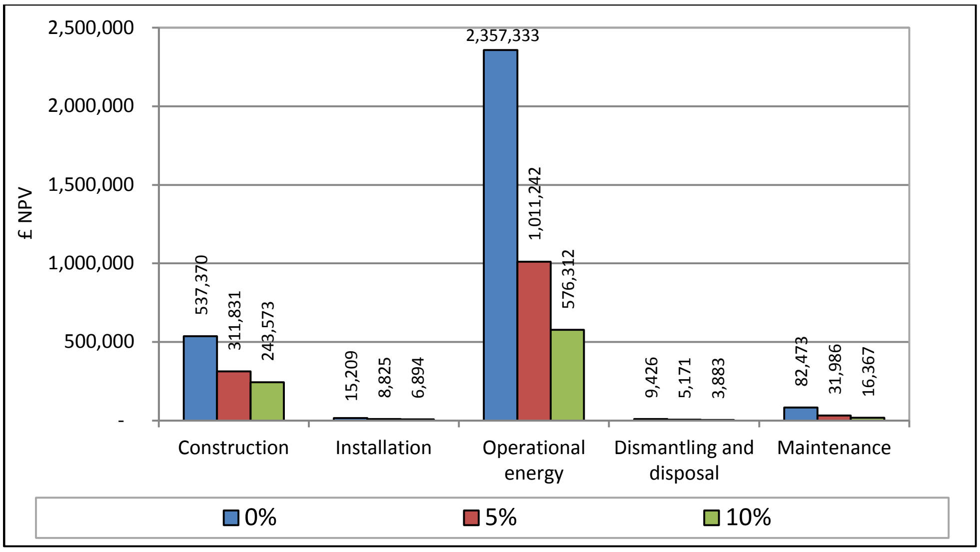


Figure 89 Life cycle costs of the electric panel system over the 40 year lifetime showing contribution of life cycle stages.

[Discounting rates of 0%, 5% and 10% shown].

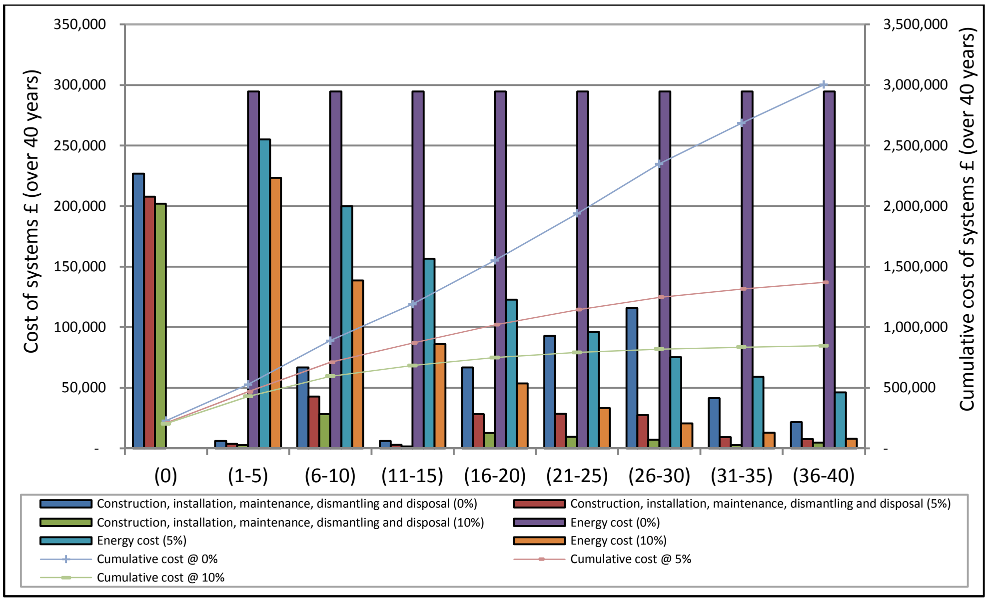


Figure 90 Life cycle costs of the electric panel system showing a breakdown of costs by 5-year periods and cumulative total for the 40 year lifetime using 0%, 5% and 10% discounting rates.

5.2.2 Electric storage system

The electric storage system uses both standard rate and cheap rate electricity and similar to the panel system shares the lighting and appliances supply network for the household. The life cycle costs of the electric storage system were estimated at £2,824,159 at 0% discounting rate. When discounting rates of 5% and 10% are applied the NPV of the system is estimated at -£1,332,533 and -£856,055 respectively - see Table 28. In a similar manner to the electric panel system, the electric storage does not generate a direct commercial return but relies on suppliers to provide the electricity required by the system.

The life cycle stage results are shown in Figure 91; the important aspects of the life cycle costing are now discussed in detail. The highest life cycle cost is the operational energy stage at approximately £2,105,000 (0% discounting); however, the system benefits from a cost reduction in electricity supplied over the 40 years through its use of cheaper off-peak electricity by the storage and immersion heaters during their recharging at night. The next largest cost is construction at £590,100 or 21% of total costs - three components are identified that incur the largest costs: the electric storage heaters, extra electrical wiring and hot water storage cylinders. Installation costs are just under 1% of the overall costs and reflect the moderate costs of electric storage heaters and the associated electricity supply system installation. Renewal costs that are included in the construction stage are estimated at £191,500 or 7% of the overall costs – this demonstrates the longevity of this particular system especially storage heaters used. The system is low maintenance at only £90,500 or 3% of life cycle costs, with minimal overall decommissioning and disposal costs at 0.4%.

Results from the LCC for the electric panel system show the initial system purchase and installation cost to be £285,387 or £81 per m^2 - this compares to Poyry et al (2009) and Spon's (2010b) who found that electric storage and immersion heating costs £184,140 or £48 per m^2. The difference in cost between the two approaches is due to the use of modern storage heaters in this study and the inclusion of the overall system wiring in the calculations.

Table 28 Life cycle cost inventory data for electric storage system.

Cost type	Item	Cost over 40 years £ [NPV @ 0%]	Cost over 40 years £ [NPV @ 5%]	Cost over 40 years £ [NPV @ 10%]
Construction	Storage heaters	226,220	149,394	121,552
	Common electric system wiring	69,300	42,667	36,636
	In-house wiring	99,200	61,076	52,443
	Immersion heaters	14,880	8,267	5,920
	Hot water cylinders	103,177	66,823	56,350
	Other: materials and equipment*	43,897	21,631	13,732
	Other: project planning and management	33,400	20,991	17,198
Installation		27,834	17,493	14,332
Operational energy	Electricity supplied (peak – day)	1,526,233	654,719	373,127
	Electricity supplied (off peak – night)	578,446	248,140	141,416
Dismantling & disposal		11,102	6,966	5,701
Maintenance	Including operation and administration	90,470	34,366	17,648
	Total life cycle cost:	2,824,159	1,332,533	856,055

*[Valve and electronics replacement].

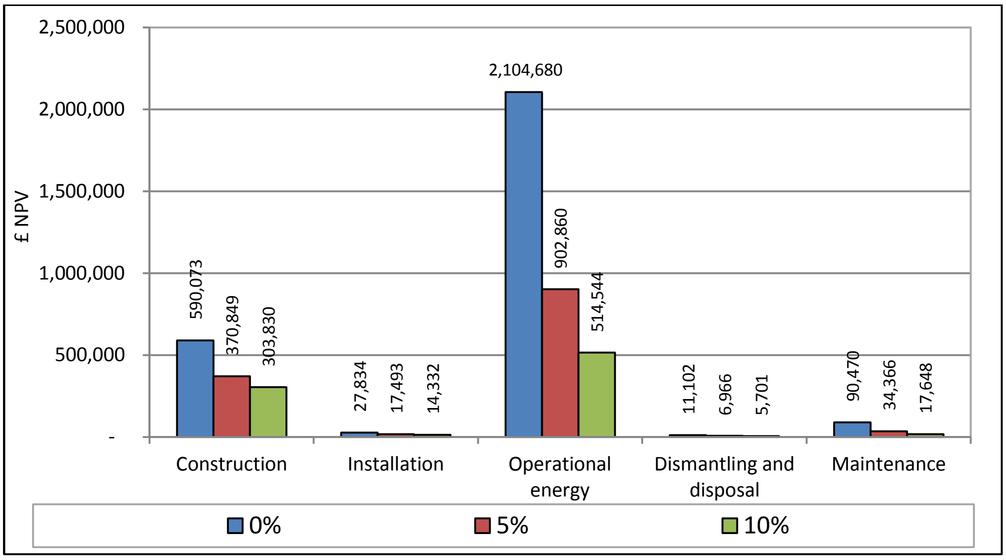


Figure 91 Life cycle costs of the electric storage system over the 40 year lifetime showing the contribution of life cycle stages.

[Discounting rates of 0%, 5% and 10% shown].

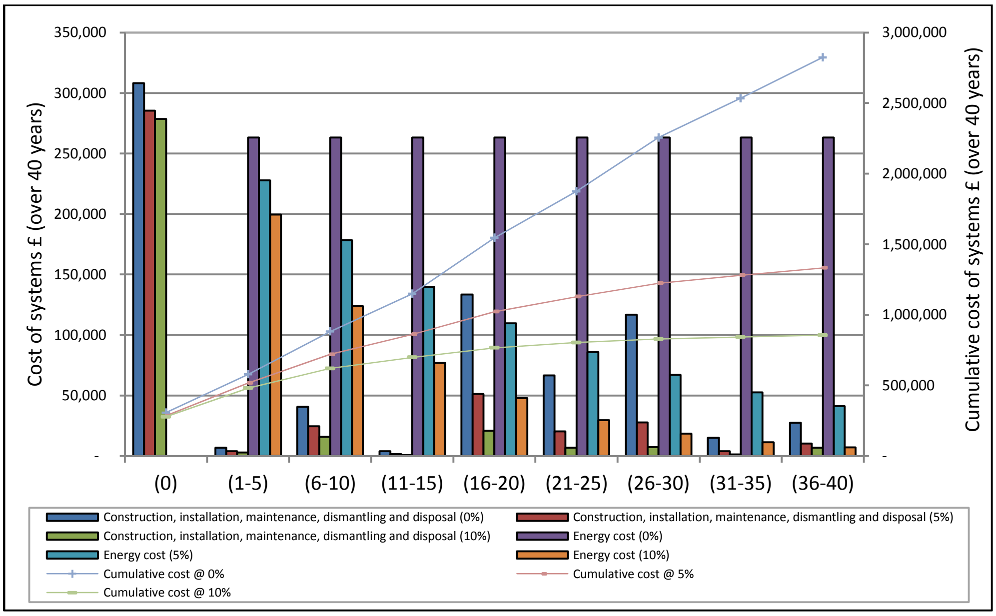


Figure 92 Life cycle costs of the electric storage system showing a breakdown of costs by 5-year periods and cumulative total for the 40 year lifetime using 0%, 5% and 10% discounting rates.

5.2.3 Air source heat pump system

The air source heat pump uses electricity both within the shared system with appliances and lighting and through an external system direct to the ASHP units located external to the apartment blocks. Overall life cycle costs for the ASHP total £3,007,406 when using a 0% discount rate. The NPV at 5% and 10% is -£1,458,285 and -£969,798 respectively – see Table 29. This system provides a commercial return through the sale of heat to apartments from the common ASHP.

The life cycle costs of each stage are represented in Figure 93. Operational energy costs amount to £1,742,400 over the 40 years and represents 58% of the overall costs and shows the overall efficiency of the ASHP system and the use of cheaper rate electricity especially for water heating. Construction costs are the next largest cost at £932,100 or 31% of total costs and are relatively high reflecting the need to install extensive hot water distribution pipes, wet systems for space heating and the ASHPs externally to the apartment block. Replacements costs that are included within the construction stage equate to 7% of overall costs during the 40 years. Maintenance costs are £237,000 or 8% of the total; the ASHP hot water supply system requires an additional support in the form of operation and administration as this is not the direct responsibility of the established utilities. Decommissioning costs and material disposal is estimated at £19,500 representing only 0.7% of total costs.

Figure 94 compares the life cycle costs of the system over five year increments. A peak in the years (16-20) and (26-30) coincides with the replacement of the ASHP and the latter for the replacement of the common water system.

Results from the overall ASHP system LCC show the initial system purchase and installation cost to be £446,729 or £127 per m^2 – few direct costs are available for comparison as only a small number of schemes have been constructed to date and costing data is confidential.

Table 29 Life cycle cost inventory data for ASHP system.

Cost type	Item	Cost over 40 years £ [NPV @ 0%]	Cost over 40 years £ [NPV @ 5%]	Cost over 40 years £ [NPV @ 10%]
Construction	ASHP	214,914	122,673	92,893
	Common interconnecting pipework	105,460	64,931	55,752
	Wet heating systems	130,200	130,200	130,200
	Immersion heaters	14,880	8,267	5,920
	Hot water cylinders	91,888	63,489	55,308
	Common block electric system	69,300	42,667	36,636
	Other: materials and equipment*	290,040	89,365	44,219
	Other: project planning and management	84,734	52,159	42,093
Installation		76,260	46,943	37,884
Operational energy	Electricity supplied (peak – day)	605,596	251,336	138,119
	Electricity supplied (off peak – night)	307,014	131,703	75,058
	Electricity supplied (commercial)	884,740	379,532	216,298
	RHI	-55,000	-34,243	-23,394
Dismantling & disposal		19,509	11,365	8,848
Maintenance	Including operation and administration	237,171	97,898	53,964
	Total life cycle cost:	3,007,406	1,458,285	969,798

*[Pumps, valves and electronics replacement and wet system protection fluid].

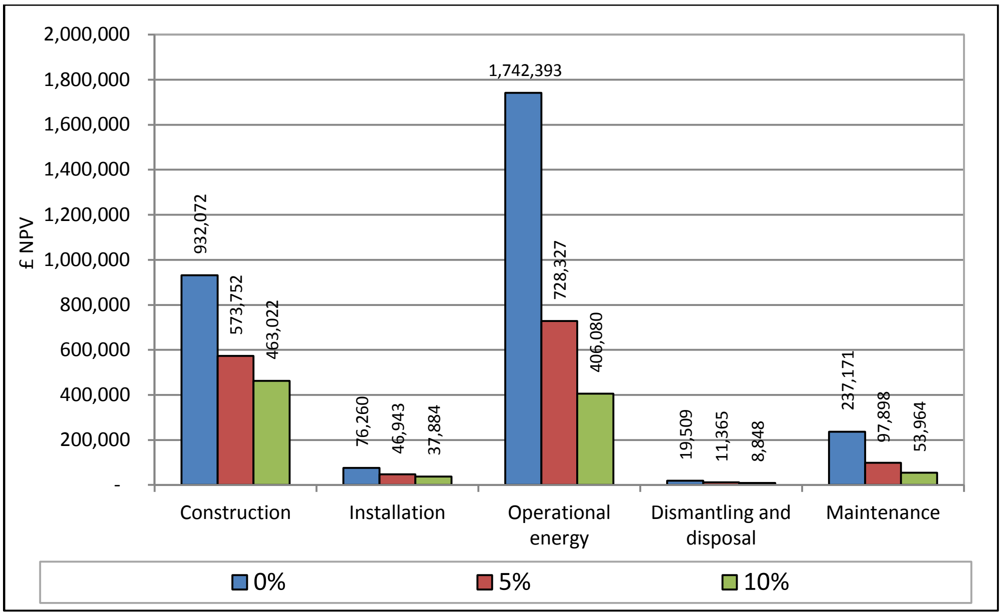


Figure 93 Life cycle costs of the ASHP system over the 40 year lifetime showing the contribution of life cycle stages

[Discounting rates of 0%, 5% and 10% shown].

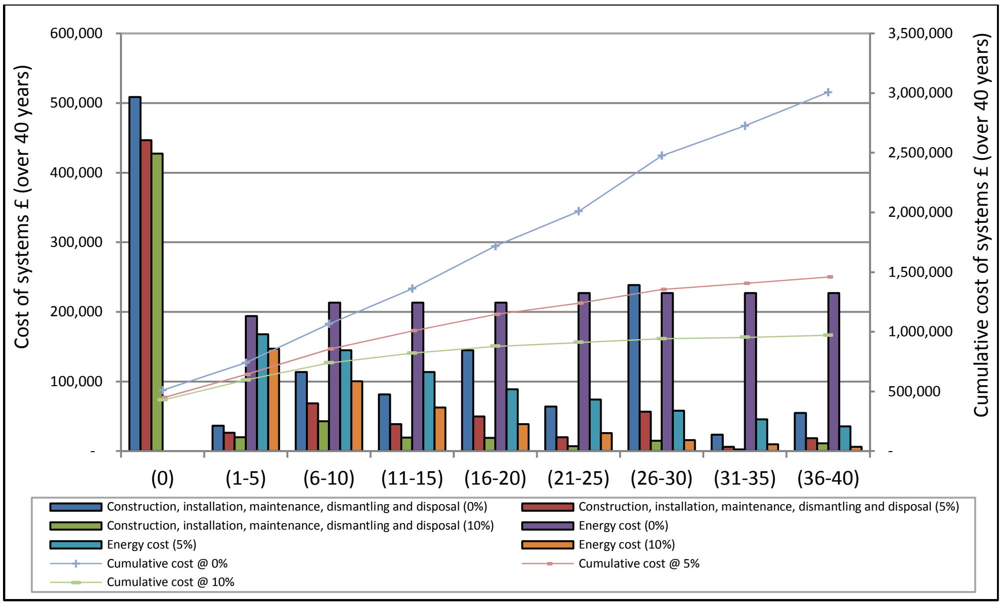


Figure 94 Life cycle costs of the air source heat pump system showing a breakdown of costs by 5-year periods and cumulative total for the 40 year lifetime using 0%, 5% and 10% discounting rates.

5.2.4 Gas boiler system

The gas boiler system uses natural gas from an extensive piped system and electricity to drive the boiler and pumps from the common electricity supply to each apartment. The life cycle costs of the gas boiler system at 0% discount rate is £2,510,373. When discount rates of 5% and 10% are applied, the NPV is estimated at -£1,211,450 and -

£787,992 respectively – see Table 30. The gas boiler system does not generate a direct return but uses natural gas and electricity from suppliers through their supply networks.

The largest contributor to life cycle costs is the operational energy especially natural gas at 47% of the overall costs based on 0% discounting rate – see Figure 95. Construction costs, the second highest contributor, are relatively high at 25% or £630,894 of life cycle costs, reflecting the difficulty of installation of the individual gas boilers, the required ventilation flue for each and the gas supply pipe system within the block and apartments. Components incurring the largest costs during construction include: the wet heating system and the individual gas boilers. The wet system represents over 45% of the initial costs for the gas system. The maintenance costs are also high for this system at 25%, due to the requirement for regular servicing and inspections of the gas boilers. Decommissioning costs are moderate considering the quantity of material within the gas boiler system and its final disposal – costs are £16,541 representing only 0.7% of the life cycle costs again at 0% discounting factor.

Figure 96 represents the costs at different discounting rates; significant expenditure is made approximately every ten years and relates to the replacement of the gas boilers or major parts within the boilers.

Results for the gas system from the overall LCC show the initial system purchase and installation cost to be £291,123 or £83 per m^2 - this compares to Spon’s (2010b) who found that a typical gas system costs £230,560 or £60 per m^2 for an apartment block of similar size and floor area. The difference in costs here relates to the inclusion of the gas supply pipe system and project management costs.

Table 30 Life cycle cost inventory data for gas boiler system

Cost type	Item	Cost over 40 years £ [NPV @ 0%]	Cost over 40 years £ [NPV @ 5%]	Cost over 40 years £ [NPV @ 10%]
Construction	Gas boilers	198,400	110,220	78,938
	Wet heating systems	130,200	130,200	130,200
	Gas supply pipes	68,000	44,040	37,138
	Wet system protection fluid	24,800	12,286	7,997
	Other: materials and equipment*	153,128	66,083	35,883
	Other: project planning and management	57,354	36,240	28,991
Installation		45,883	28,992	23,193
Operational energy	Electricity supplied (peak – day)	195,351	83,801	47,759
	Gas supplied	984,022	422,124	240,570
Dismantling & disposal		16,541	10,207	8,032
Maintenance	Including operation and administration	636,694	267,257	149,291
	Total life cycle cost:	2,510,373	1,211,450	787,992

*[Valve, electronics and radiator replacement over 40 years].

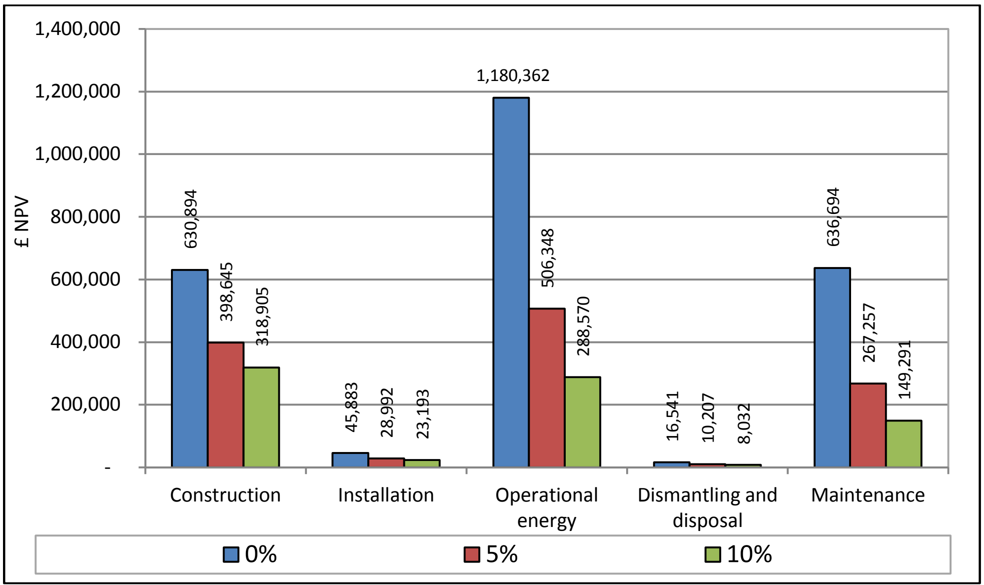


Figure 95 Life cycle costs of the gas boiler system over the 40 year lifetime showing the contribution of life cycle stages.

[Discounting rates of 0%, 5% and 10% shown].

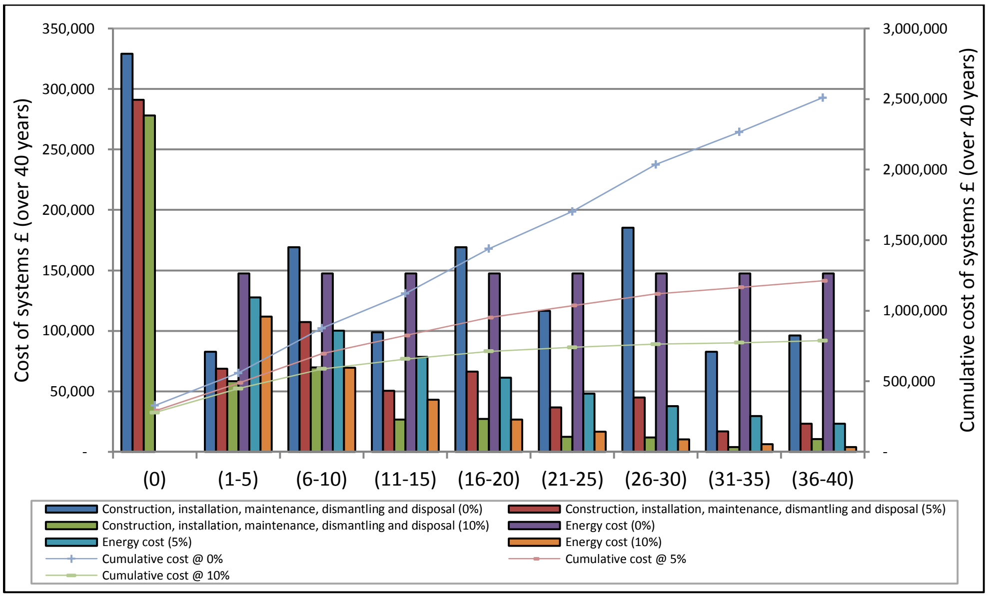


Figure 96 Life cycle costs of the gas boiler system showing a breakdown of costs by 5-year periods and cumulative total for the 40 year lifetime using 0%, 5% and 10% discounting rates.

5.2.5 Combined gas and electric system

The combined gas and electric system uses two separate networks to provide heating for households. Life cycle costs of this system are estimated at £2,648,929 using a discount rate of 0%. A summary of the cost breakdown for different discounting rates is shown in Table 31 with NPV of -£1,240,627 and -£695,610 respectively for 5% and 10% rates. The combined system provides a direct return based on the heat for domestic hot water from the centralised boiler to each apartment – however overall this is very small.

The key contributor to life cycle costs is the operational energy forming 67% of the overall costs – see Figure 97 and shows the lower cost and efficiency of natural gas and centralised boilers used for the hot water supply but the higher premium for the space heating standard rate electricity. Construction costs are elevated reflecting the difficulty of installation of the hot water supply system; however this is negated with the relative ease of installation for the electric panel system for the space heating. The components incurring the largest costs during construction include: the electric panels, extra electrical wiring and the centralised gas boilers. Renewal costs during the 40 years are estimated at £125,130 and decommissioning and disposal costs at £22,615.

The breakdown of costs over five year periods is shown in Figure 98 and highlights the significant expenditure in years (26-30) which relates to the renewal of the common wet heating system and gas supply pipe.

Results for the combined system from the LCC show the initial system purchase and installation cost to be £282,790 or £81 per m^2 - little comparative data is available for this particular system.

Table 31 Life cycle cost inventory data for combined gas and electric system.

Cost type	Item	Cost over 40 years £ [NPV @ 0%]	Cost over 40 years £ [NPV @ 5%]	Cost over 40 years £ [NPV @ 10%]
Construction	Electric panels	176,500	93,717	64,706
	Common electric system wiring	69,300	42,667	36,636
	In house electric wiring	99,200	61,076	52,443
	Centralised gas boilers	50,700	28,939	21,914
	Gas supply pipes	21,090	12,985	11,149
	Common wet heating systems	105,460	64,931	55,752
	Other: materials and equipment*	51,235	26,343	18,193
	Other: project planning and management	54,213	31,260	24,678
Installation		58,579	33,834	26,636
Operational energy	Gas supplied	345,989	148,422	84,585
	Electricity supplied	1,435,672	615,870	350,988
Dismantling & disposal		22,615	12,621	9,687
Maintenance	Including operation and administration	158,376	67,962	38,243
	Total life cycle cost:	2,648,929	1,240,627	795,610

*[Valve, electronics and replacement over 40 years].

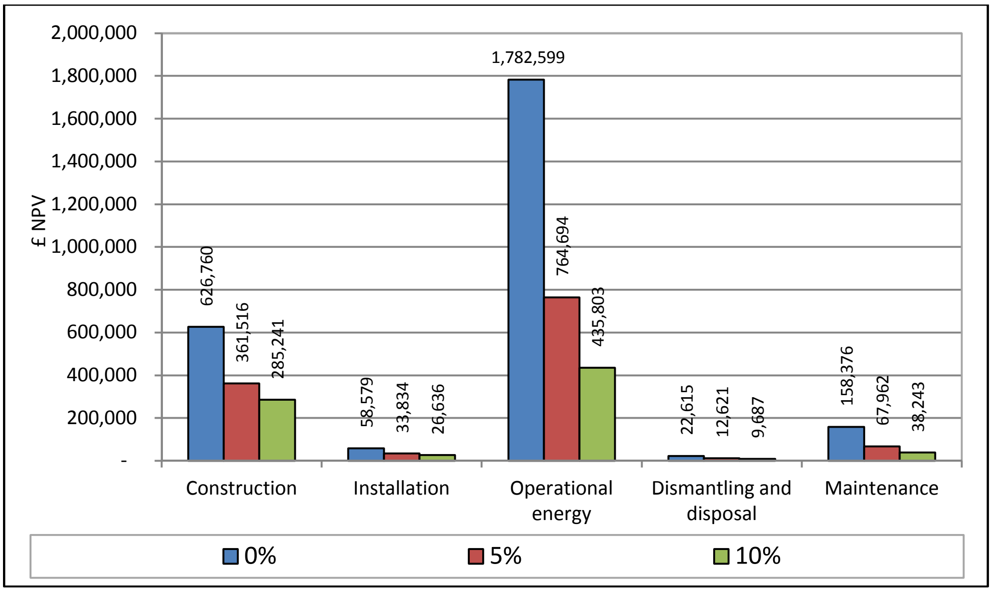


Figure 97 Life cycle costs of the combined gas and electric system over the 40 year lifetime showing the contribution of life cycle stages.

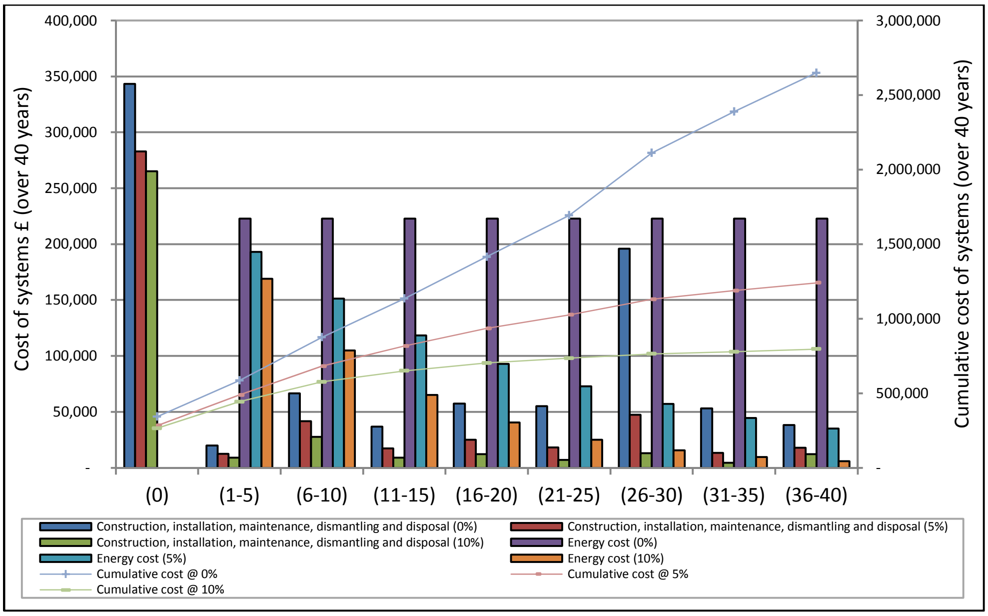


Figure 98 Life cycle costs of the combined gas and electric system showing a breakdown of costs by 5-year periods and cumulative total for the 40 year lifetime using 0%, 5% and 10% discounting rates.

5.2.6 District heating system

The district heating system consists of natural gas boilers in an energy centre, an underground hot water distribution system and apartment block wet heating system controlled by heat stations within each apartment. The district heating system has an estimated life cycle cost of £3,606,472 at a discount rate of 0%. The NPV of the system is estimated at -£1,942,457 and -£1,413,391 using discount rates of 5 and 10% respectively – see Table 32. This system provides a commercial return on the heat supplied for both space and water heating whereas electricity is supplied from the external electricity grid.

The district heating system uses natural gas as it main fuel for heating, while electricity is used for water pumping and system control. Operational energy costs in this system consist of only (25%) of the total life cycle costs. The boilers use natural gas that is supplied on a commercial contract basis. Heat metering is employed – this having been determined to be cost effective to a 20% saving (DECC, 2012b) particularly for purpose built flats using district heating. Nevertheless, operation energy costs are estimated at £914,817 per 40 year showing the moderate comparative cost of natural gas as shown in Figure 99. It should be noted that here a responsibility for the operation and maintenance of a system is provided to a second organisation away from established utilities. Changes in energy costs are likely to be reviewed and amended often in relation to a smaller group of householders than an established utility company.

This system contains major equipment including: an energy centre with modulating gas boilers, a hot water distribution system and apartment heat stations or heat interface units that contain a heat meter. The three components incurring sizeable costs include: district heating distribution pipe network, energy centre building and the apartment heat stations - further costs are incurred for system maintenance and equipment replacement; the recurring cost and cumulative cost timeline is shown in Figure 100. Construction costs are notably high £1,144,000 due to the requirement for an energy centre containing the gas boilers, pumps and storage, and the extensive excavation of the hot water distribution pipes. Overall installation costs are also high at £153,273. System and component renewal costs during the 40 years are also extensive equating to approximately half the initial construction costs – this is due to the maintenance and repair of this equipment heavy hot water system.

Decommissioning and end of use stage have varying impacts – the distribution pipes are likely to remain in the ground and buried whereas the metallic pipes would be removed and recycled. Decommissioning and disposal costs are £29,701 although pipes in each block and the wet heating system can be reclaimed the water distribution system would remain buried.

Results from the overall LCC for the district heating system show that the initial system construction and installation cost to be £822,915 per apartment block or £234 per m^2 - when this is compared to (Energy, 2010b) calculations for a district energy scheme for three blocks based on biomass and gas boilers - costs are £1,857,850 or £362 per m^2. In addition, (EST, 2008; Poyry et al., 2009) suggest that district heating costs for high rise apartment blocks are £2,500 and £4,800 per flat respectively – however costs vary considerably depending on the actual capital costs included.

Table 32 Life cycle cost inventory data for district heating system.

Cost type	Item	Cost over 40 years £ [NPV @ 0%]	Cost over 40 years £ [NPV @ 5%]	Cost over 40 years £ [NPV @ 10%]
Construction	Main gas boilers	29,160	16,644	12,604
	Wet heating systems	130,200	130,200	130,200
	Gas supply pipes	30,000	19,430	16,384
	Energy centre	175,000	107,746	92,514
	Hot water cylinders	103,177	66,823	56,350
	Heat stations	223,200	153,661	128,189
	Distribution network	195,000	168,333	158,872
	Buffer/storage tank	80,000	51,812	43,692
	Other: materials and equipment*	56,144	33,677	25,752
	Other: project planning and management	122,618	89,796	79,745
Installation		153,273	112,245	99,681
Operational energy	Electricity supplied	353,039	151,445	86,310
	Gas supplied	561,778	240,990	137,341
Dismantling & disposal		29,701	21,496	18,983
Maintenance	Including operation and administration	1,364,182	578,159	326,774
	Total life cycle cost:	3,606,472	1,942,457	1,413,391

*[Valve, electronics and radiator replacement over 40 years].

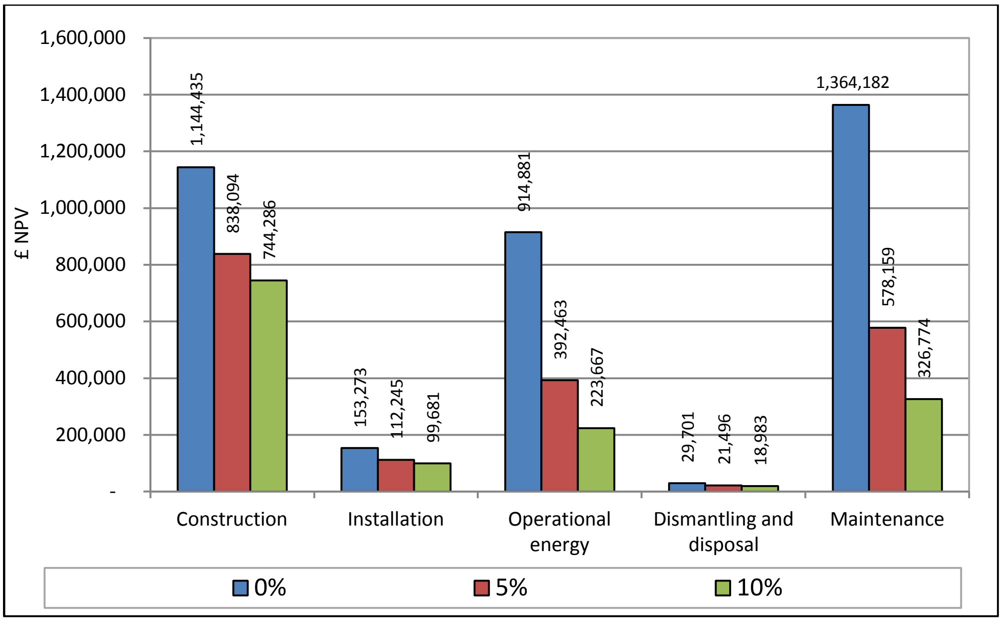


Figure 99 Life cycle costs of the district heating system over the 40 year lifetime showing the contribution of life cycle stages.

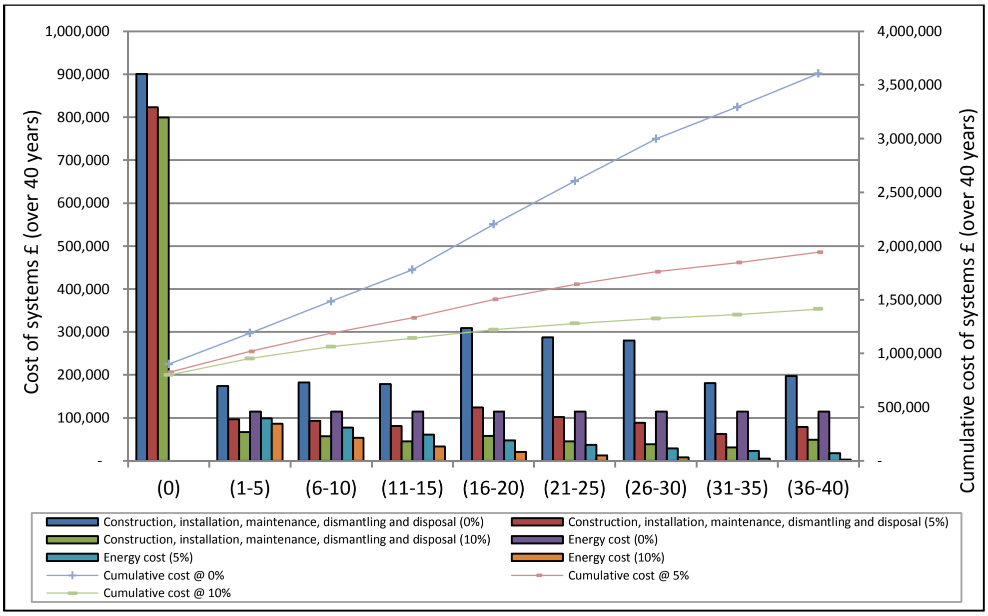


Figure 100 Life cycle costs of the district heating system showing a breakdown of costs by 5-year periods and cumulative total for the 40 year lifetime using 0%, 5% and 10% discounting rates.

5.2.7 Community CHP system

The community CHP system is constructed and operated in a very similar manner to the district heating system described previously but with the addition of a combined heating and power unit. Overall, the life cycle costs of the community CHP system are estimated at £3,702,119 using a 0% discounting rate; life cycle costs using a 5 and 10% discount rate show NPV's of -£2,065,549 and -£1,544,113 respectively further details are shown in Table 33.

Maintenance costs for this system are high £1,633,000 reflecting the need to maintain an extensive system including the energy centre, pipelines and apartment heat stations – see Figure 101. The construction cost is the second highest reflecting the situation described earlier for the district heating system but also due to the extensive requirements of the CHP unit itself including - foundations, electrical and mechanical systems. The main components incurring sizeable costs include: district heating distribution pipe network, energy centre building, apartment heat stations and CHP unit. Renewal costs during the 40 years are also high equating to approximately 89% of the initial construction costs – see Figure 102. Installation costs associated with the system are comparatively high at approximately £188,000. Regarding operational energy - the CHP unit provides hot water to the distribution pipe system and electricity to the apartment block common system; the CHP unit and associated gas boiler are supplied with natural gas on commercial rates and generate a return on the provision of both heat and electricity. Operation energy costs are estimated at £457,500 per 40 years demonstrating the cost of natural gas and the income from electricity and heat generated. Decommissioning and disposal costs amount to £36,700 – this equipment and material heavy system has impacts both in terms of disposal costs but also scrap costing and benefit – in a similar manner to the district heating system, the distribution pipes are likely to remain in the ground and buried whereas the metallic pipes would be removed and recycled.

Results for the community CHP system from the overall LCC show initial system purchase and installation costs at £991,686 or £282 m^2 for one apartment block – comparison with a similar scheme supplying three apartment blocks indicates an initial construction cost of £1,990,400 or £388 per m^2 (Energy, 2010b). Elsewhere (BioRegional, 2012) suggest a cost per flat of £10,125 for a district heating system with CHP or £14,611 per flat including a “light” retrofit – when matched to this case study the cost is between £179 and £257 per m^2. It should be noted that costs can vary dramatically depending on number of flats and blocks included and the extent of the district heating system.

Table 33 Life cycle cost inventory data for combined heat and power system.

Cost type	Item	Cost over 40 years £ [NPV @ 0%]	Cost over 40 years £ [NPV @ 5%]	Cost over 40 years £ [NPV @ 10%]
Construction	Main gas boilers	29,160	16,644	12,604
	CHP unit	153,000	105,332	87,871
	Wet heating systems	130,200	130,200	130,200
	Gas supply pipes	30,000	19,430	16,384
	Energy centre	195,000	107,746	92,514
	Hot water cylinders	103,177	66,823	56,350
	Apartment heat stations	223,200	153,661	128,189
	Main block heat station	30,000	20,653	17,230
	Distribution network	195,000	168,333	158,872
	Buffer/storage tank	80,000	51,812	43,692
	Power cables	60,000	36,941	31,719
	Other: materials and equipment*	26,146	25,337	19,096
	Other: project planning and management	150,578	108,346	95,365
Installation		188,223	135,433	119,206
Operational energy	Electricity supplied	353,039	151,446	86,310
	Gas supplied	726,738	311,755	177,671
	FIT	-631,510	-270,903	-154,390
Dismantling & disposal		36,691	26,134	22,888
Maintenance	Including operation and administration	1,623,477	700,426	402,342
	Total life cycle cost:	3,702,119	2,065,549	1,544,113

*[Valve, electronics and system protection fluid replacement over 40 years].

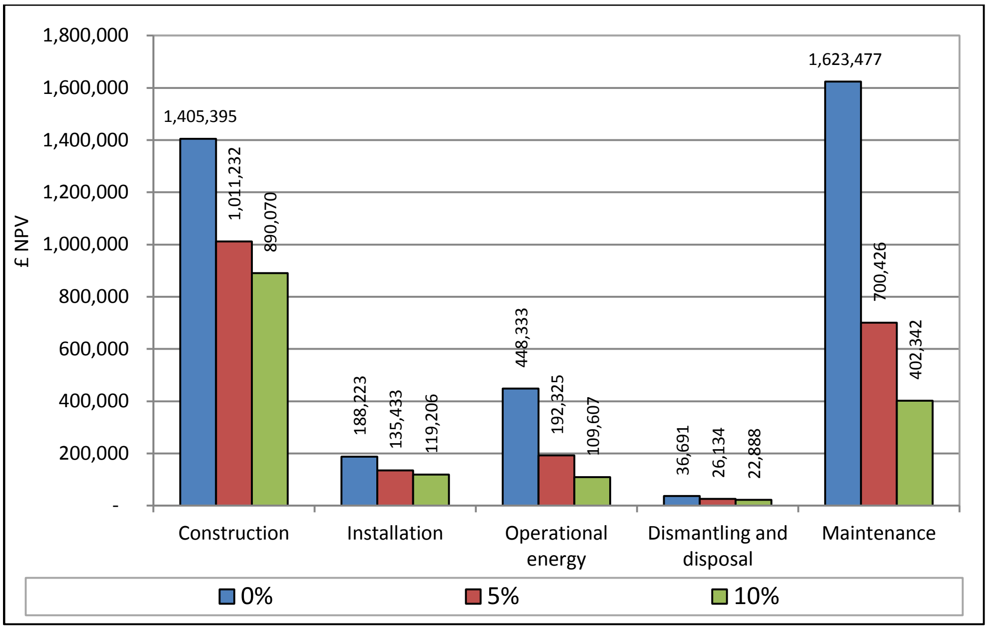


Figure 101 Life cycle costs of the combined heat and power system over the 40 year lifetime showing the contribution of life cycle stages.

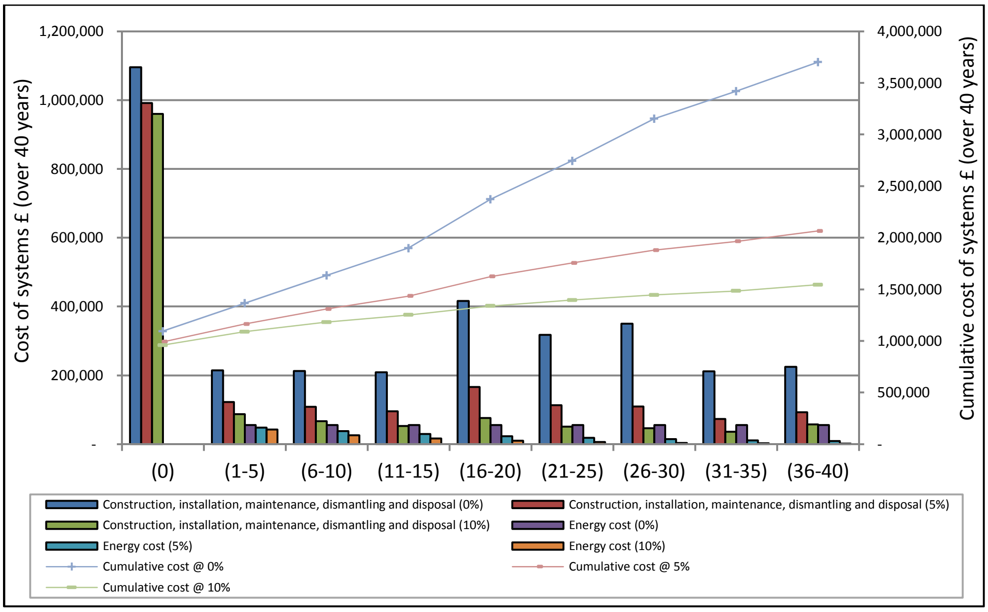


Figure 102 Life cycle costs of the combined heat and power system showing a breakdown of costs by 5-year periods and cumulative total for the 40 year lifetime using 0%, 5% and 10% discounting rates.

5.2.8 Solar thermal and gas system

The life cycle costs of the solar thermal and gas system are estimated and the results are shown in Figure 103. Charging for solar thermal heat is by apportionment of heat charges or points based systems whereas gas is metered and charged accordingly. Overall, the life cycle costs of the electric panel system are estimated at £3,452,686 per

40 year when using a 0% discounting rate; the life cycle costs for other NPV rates are shown in Table 34. Construction and renewal forms the highest costs at £1,247,200 reflecting the extensive installation and high costs of solar thermal panels and the aluminium frames – see Figure 103. Three particular system components incur sizeable construction costs: solar thermal panels, individual gas boilers, and the wet heating systems - renewal costs during the 40 years are however moderate equating to approximately 85% of the initial construction costs.

The second highest costs are for the operational energy supplied at approximately £1,147,000, indicating the comparatively low cost of gas and thermal energy from the solar panels. Figure 104 shows the impacts of energy and incentives over the 40 year period through an increase in costs after year twenty. The third largest cost is for maintenance £868,000 and principally covers the regular servicing of individual gas boilers and to a less extent the solar thermal array.

Life cycle costing results for the district heating system show the initial system purchase and installation cost to be £675,186 or £192 m^2. Little data is available for community solar thermal systems with supporting gas boilers - (Croxford and Scott, 2006) identified an initial construction cost of £13,900 for a community solar thermal system feeding 18 flats.

Table 34 Life cycle cost inventory data for solar thermal and gas system.

Cost type	Item	Cost over 40 years £ [NPV @ 0%]	Cost over 40 years £ [NPV @ 5%]	Cost over 40 years £ [NPV @ 10%]
Construction	Solar thermal panels	250,000	161,913	136,537
	Interconnecting pipework	105,460	68,301	57,597
	Hot water cylinders	103,177	66,823	56,350
	Gas boilers	198,400	110,220	78,938
	Gas supply pipes	68,000	44,040	37,138
	Wet heating system	130,200	130,200	130,200
	Control modules for apartments and panels	62,000	34,444	24,668
	Electronics replacement	86,420	40,534	24,256
	Other: materials and equipment*	125,634	67,205	47,003
	Other: project planning and management	117,913	75,622	62,008
Installation		142,358	90,865	73,927
Operational energy	Electricity supplied	184,679	79,223	45,150
	Gas supplied	865,361	371,220	211,560
	Solar thermal	121,821	28,644	7,717
	RHI	-24,441	-15,230	-10,404
Dismantling & disposal		47,588	29,720	23,832
Maintenance	Including operation and administration	868,116	705,144	655,557
	Total life cycle cost:	3,452,686	2,088,888	1,662,034

*[Valve and system protection fluid replacement over 40 years].

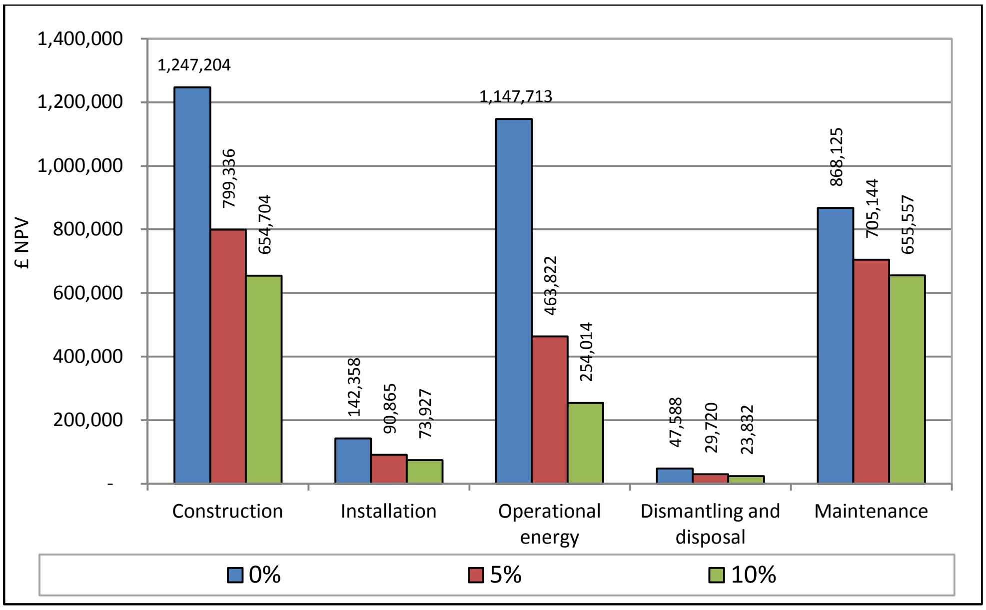


Figure 103 Life cycle costs of the solar thermal and gas system over the 40 year lifetime showing the contribution of life cycle stages.

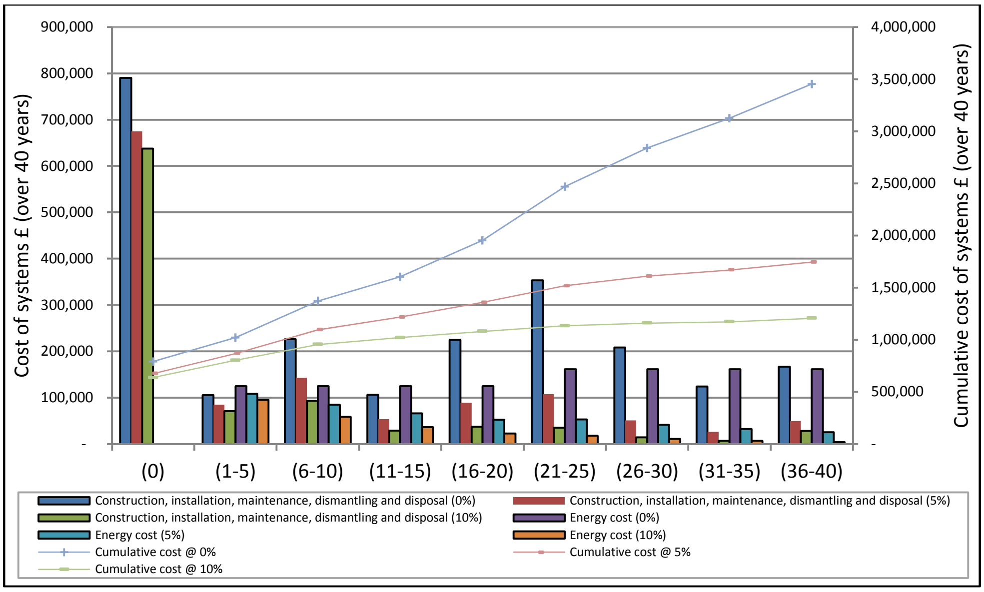


Figure 104 Life cycle costs of the combined solar and gas system showing a breakdown of costs by 5-year periods and cumulative total for the 40 year lifetime using 0%, 5% and 10% discounting rates.

5.3 Comparison of the LCC of different heat-providing systems

The life cycle costs of the heating systems are compared in Figure 105. Overall, the LCC of the gas boiler system is the lowest at £2,510,400 over 40 years, benefiting from both relatively low fuel costs £1,180,400 and moderate construction £630,900 and installation costs £45,900. At £2,650,000 the combined gas and electric system is the next least expensive option, as it does not require either a wet system for space heating or hot water storage in apartments. The highest overall cost is found for the CHP at

£3,702,000 and district heating system with £3,606,000. Although they both benefit from relatively low energy costs, they are subject to high initial construction and on-going maintenance costs. Figure 106 compares the LCC costs of the systems for five-year periods over 40 years after initial construction. As can be seen, costs are relatively even over each period for all systems and the gas boiler and combined system following a similar cumulative line throughout the 40 years.

The life cycle renewal costs are lowest for the Electric storage system at £400,000 and highest for the CHP system at £2,121,000. The latter is due to the extensive district heating systems with complex equipment and the range and number of heat stations located in apartments and blocks.

As indicated in Figure 107, the relative ranking of the eight systems stay exactly the same across the range of discount factors - 0%, 5% and 10%. However, as the discount rate increases, the gas boiler, combined gas and electric and electric storage and panel systems NPV costs converge. Selecting a higher discount rate places greater emphasis on short-term costs and low discount rates increase the contribution of longer-term costs. The costs are discussed in more detail by life cycle stage next and are considered at 0% discounting rate throughout.

Construction – the largest construction and renewal costs are shown by the CHP, solar thermal and gas and district heating systems at £1,405,000, £1,247,000 and £1,145,000 respectively and contrast with the lowest cost; the electric panel system at £537,000. The high cost of the centralised type systems is due to the extensive pipe network and associated equipment required to provide heat from a central energy location. The high cost equipment and components for each system and the percentage of the LCC are shown below:

- *Electric panel* – electric panels (6%), hot water cylinders (3.5%);
- *Electric storage* – storage heaters (8%), hot water cylinders (3.7%);
- *ASHP* – heat pumps (7.1%), wet heating systems (4.3%), interconnecting pipework (3.5%);
- *Gas boiler* – gas boilers (8%), replacements (6.1%), wet system (5%);

- *Combined gas and electric* – electric panels (6.6%), interconnecting pipework (4%);
- *District heating* – heat stations (6.2%), hot water underground network (5.4%), energy centre (5%);
- *CHP* – heat stations (6%), energy centre (5.3%), hot water underground network (5.3%), chp units (4%); and
- *Solar thermal and gas* – thermal panels (7.2%), gas boilers (5.8%).

The cost of equipment and components for hot water storage for each system is shown in Figure 108. Good practice suggests the heating of water more efficiently – one way is to use instantaneous water heating rather than storage (Miller, 2005). The study shows, the highest life cycle cost of storage is for the CHP £204,000, district heating £183,000 and solar thermal and gas systems £165,000 and the lowest - the individual gas boiler system £15,872. Storage represents an average of 5% of the life cycle cost for the six most expensive systems.

Installation – the highest costs are made by the same systems as detailed under the construction heading with the CHP offering the highest installation costs of £188,000. Again this is due to the extensive installation requirements of pipe systems and centralised heat units, and contrast with the lowest installation costs of the electric panel system at only £15,200.

Operational energy – for five of the systems, the highest contribution to costs is from the energy used during the operation stage and ranges as follows:

- Electric panel system: 81.5%
- Electric storage system: 72.8%
- ASHP system: 58.7%
- Gas boiler system: 40.8%
- Combined system: 61.6%.

For the remaining systems - solar thermal and gas, district heating and CHP system - the contribution of the operational energy is 37.4%, 31.6% and 15.5% respectively. Substantial operational energy costs are incurred by the electric panel system at £2,358,000 over 40 years where standard rate electricity is used; the lowest cost is achieved by the CHP system at £457,500 over the lifetime with heat provided for space and water heating and electricity for wider distribution and cost reduction. The district heating £922,000 and solar thermal and gas system £1,148,000 offer comparable operational energy costs to the individual gas boiler system £1,180,000.

As mentioned previously, the life cycle costs of the heating systems in apartments will be incurred by different cost bearers, principally here, the developers, tenants and energy service companies (ESCo); this is illustrated in Table 35. While the initial construction and commissioning costs are essentially paid for by developers, any on-going maintenance, repair and replacement of equipment and parts is generally paid by the property owners, landlords, council or ESCo's directly or indirectly through service tariffs or contributions. Nevertheless, operational energy costs are normally paid for by tenants or owners, however the use of commercial rate energy supplies particularly within the ASHP, combined gas and electric, district heating, CHP and combined solar thermal and gas systems means the inclusion of intermediaries and their associated costs. The dilemmas and benefits of this approach and the wider consequences of intermediary energy supply companies are explored further in Chapter 6.

A tariff benefit is therefore often gained by service companies where energy is purchased at a lower cost and sold to householders at a premium or higher cost. The estimated costs per kWh heat delivered are given in Figure 109 and illustrate the tariff benefits considered; those supplied directly show heat from individual gas boilers cost 15.2p per kWh and from the electric-based systems between 17.0p and 18.0p per kWh. Systems supplying heat indirectly incur tariff benefits of 5.8p, 5.8p, 2.6p, 0.8p and 4.8p for the ASHP, combined gas and electric, district heating, CHP and solar thermal and gas respectively.

When life cycle operational energy costs are compared with available incentives, three systems benefit to varying degrees. The ASHP gains approximately £55,000 through the RHI over the 40 years, while the gas fuelled CHP system can claim for FIT's £631,500 although RHI is not permitted for this particular system. Finally the solar thermal and gas system benefits from the RHI £98,000 although heat is sold onto the households at a rate equivalent to natural gas so the incentive is shown positive in Figure 110. Each of the incentives was calculated for the number of years designated from the start of the system operation and therefore shows higher energy costs after the incentive scheme comes to an end – the assumption is that further schemes are not forthcoming.

The cost impacts for each system supplied with energy directly and indirectly are illustrated in Figure 110. The solar thermal system has however the added advantage of income through the RHI although this represents only 8% of operation energy cost for the system. It is worth noting that the community CHP system has opportunities to generate income through the export of generated electricity to the wholesale market although feed in tariff rates are considered relatively low (Energy, 2010b); the alternative is offsetting electricity to common apartment block demands or householders but these can be quite variable.

Decommissioning – these costs are under 0.6% of the overall costs for individual systems and between 0.7% and 1.4% for the centralised systems. More significant decommissioning cost in comparison to the other systems is found for the solar thermal and gas system £47,588 owing to the extensive materials and fittings. The equivalent costs for the stand alone electric system are lower, at £9,400 and £11,100 for the panel and storage systems, respectively.

Maintenance - the highest maintenance costs are experienced by the CHP system at £1,633,000 while the small standalone technologies and systems have a significantly lower cost, the electric panel, storage and combined gas and electric at £82,500, £90,500 and £158,000 respectively.

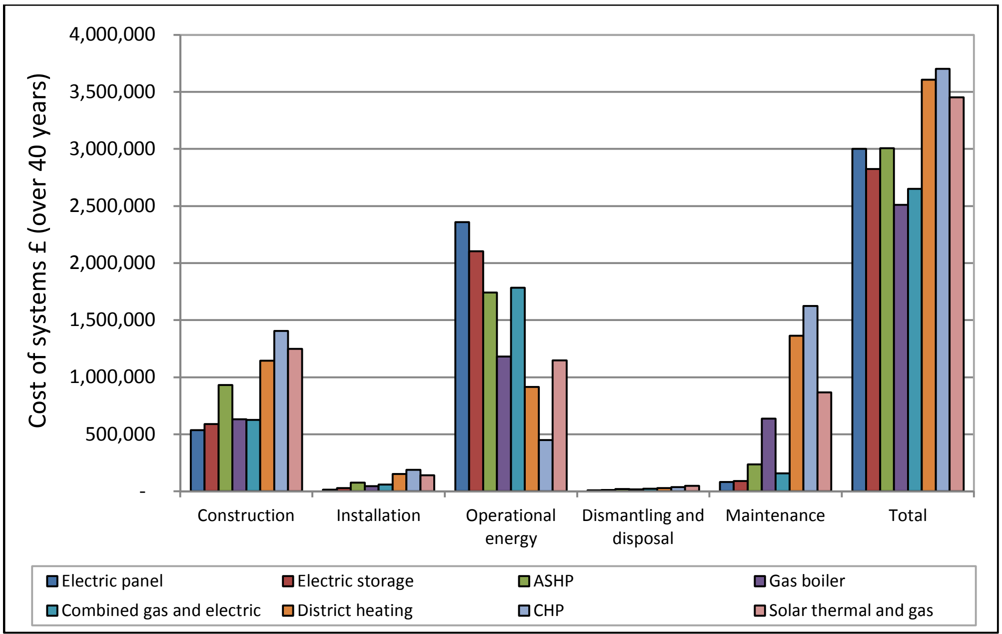


Figure 105 Comparison of the LCC for eight heating systems showing cost breakdown by life cycle stage and at 0% discounting rate.

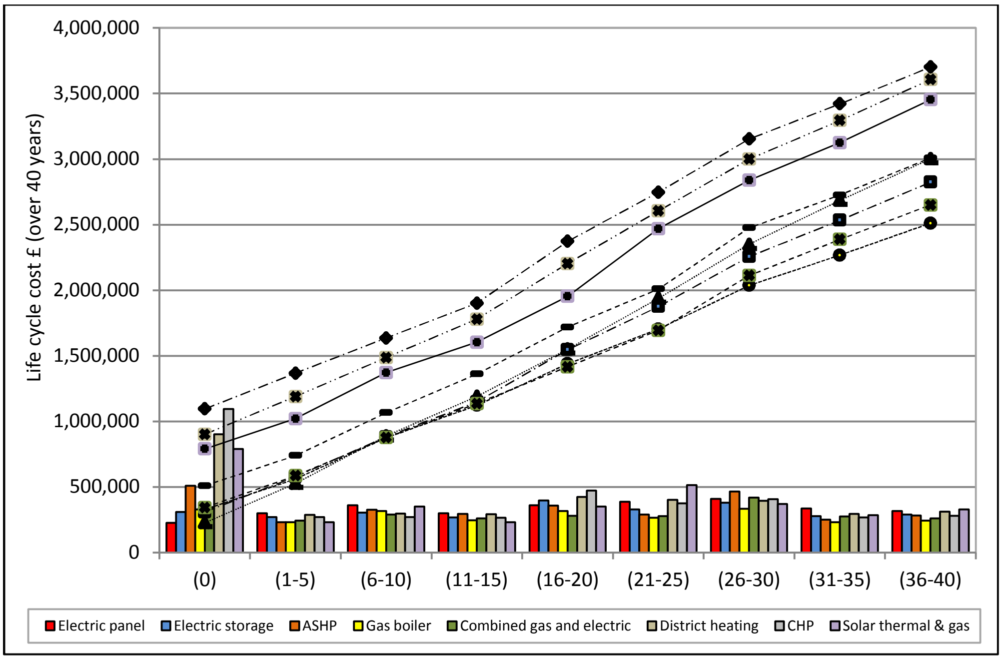


Figure 106 Life cycle cost of eight systems given a stable and consistent energy price over 40 years and shown at 0% discounting rate.

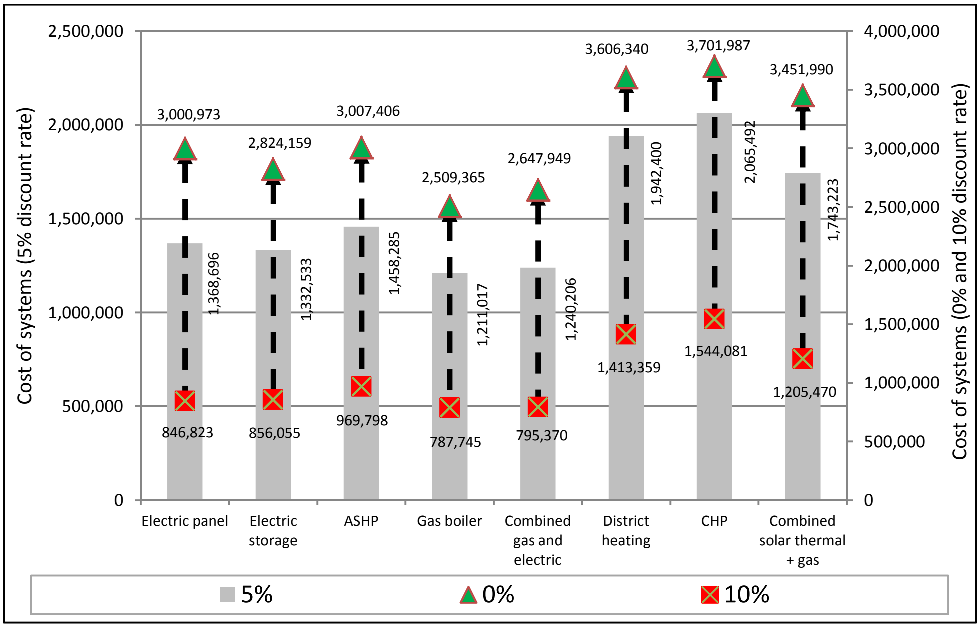


Figure 107 Life cycle costs for the eight heating systems over 40 years for different discounting factors.

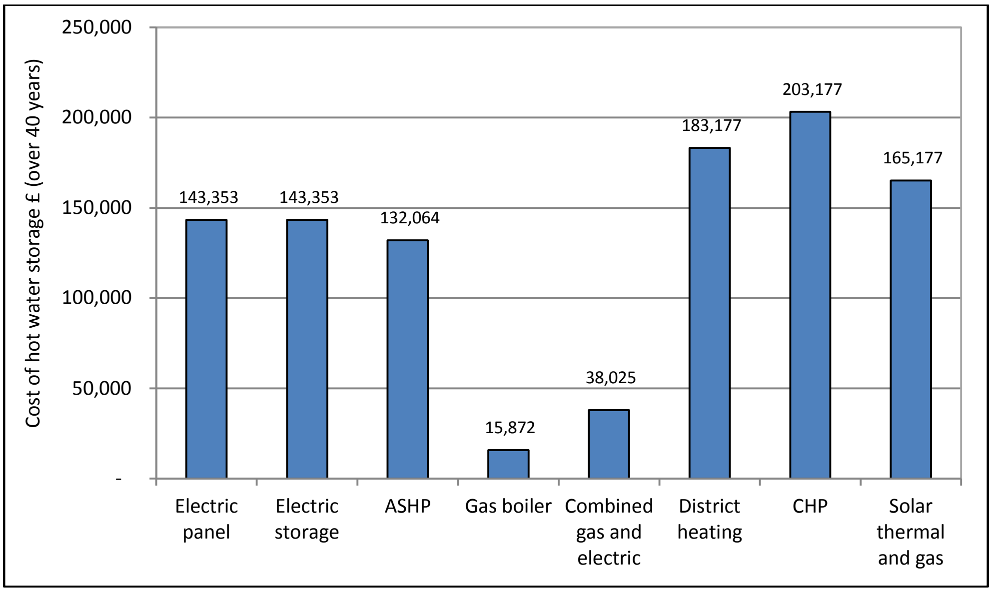


Figure 108 Comparison of hot water storage costs for the eight heat providing systems.

Table 35 Cost bearers, their involvement and activities associated with each system.

Cost bearer	Activities	Electric panel	Electric storage	ASHP	Gas boiler	Combined gas and electric	District heating	CHP district heating	Solar thermal and gas
Energy supply utility*	Electricity and gas supply and maintenance	X	X	X	X	X	X	X	X
Energy supply company	Heat supply, maintenance and repair			X		X	X	X	
Community association	Heat supply, maintenance and repair								X
Householders	Energy consumption	X	X	X	X	X	X	X	X

*Examples of energy supply utilities include: British Gas, Scottish Power, SSE.

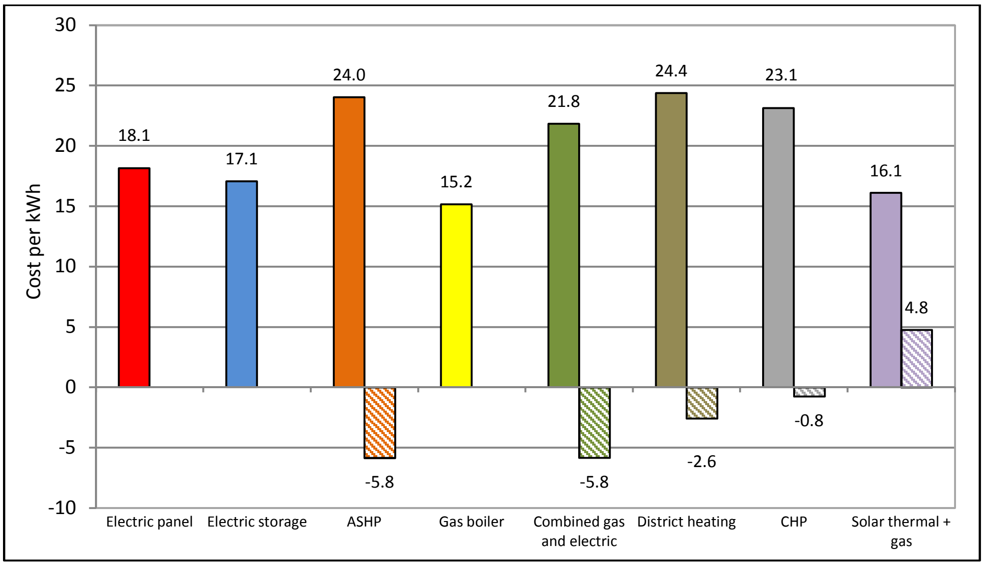


Figure 109 Cost of heat provision for heat system (pence per kWh).

[Pattern fill represents the tariff benefit for each system when energy is bought by the energy service company and sold on to the householder].

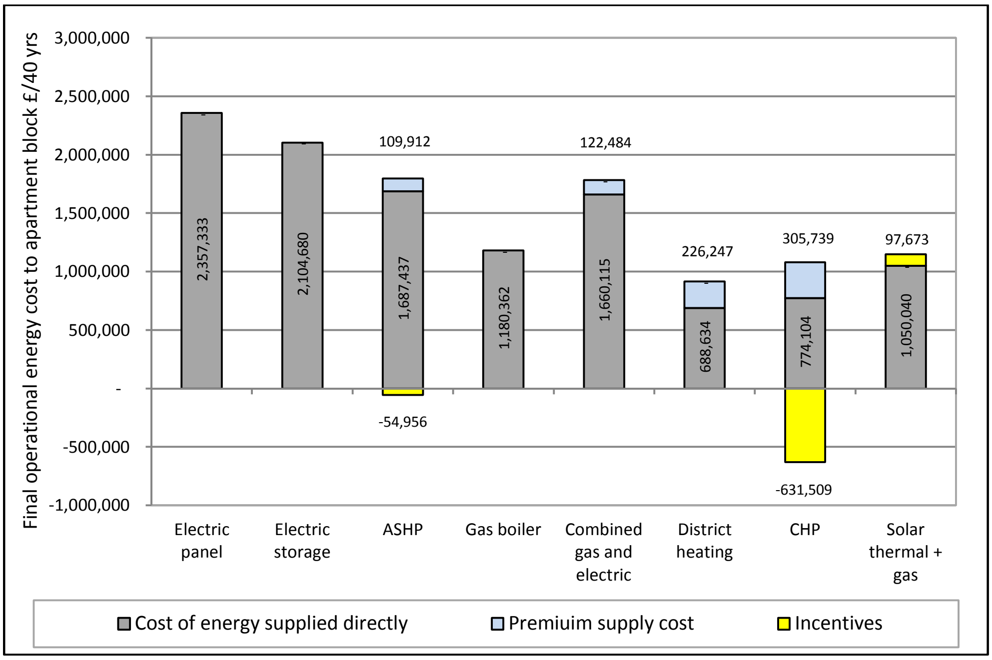


Figure 110 Operational energy cost over 40 years for the eight systems at 0% discount rate.

[Energy supplied directly includes electricity and gas supplied to the customer or householder from the national utilities. Premium supply cost is the cost of energy added by an ESCo or operating company before supply to householders. Cost of incentives includes FITs and RHI].

The following section examines through a sensitivity analysis how the costs of the heating systems would compare if some of the assumptions made so far were different.

5.4 Sensitivity analysis

5.4.1 Operational energy costs

The price and availability of fuel in the future is unpredictable. Increases over the last seven years as shown in section 2.1.2.6 and those over the last year (2013) have continued to exert pressure on household incomes. For this reason, two scenarios are explored: one where the gas prices increase with the electricity prices remaining the same Scenario 1 and another where electricity costs go up and gas prices remain the same Scenario 2. These assumptions are compared to the base case in Table 36 and the results are presented in Figure 111. As indicated in the figure, for Scenario 1, the electric based systems are largely unaffected except for the combined system that sees an increase in system costs; all other systems show cost increases. The storage heater system is now the cheapest – this is in contrast to the base case where gas boiler was the least expensive option - see Figure 105. In terms of overall system costs gas prices would need to increase by 15% to achieve parity with the electric systems if electric unit rates remain frozen at their original rate. However, for the operational energy, it would take gas prices to increase approximately 30% every five years to enable the electric based systems to closely match the energy costs of the gas boiler system.

For Scenario 2, all electric-based systems overall costs are increased markedly making the electric panel system most expensive and the storage heater a close second. The breakeven point for the transition from a more economical gas based system (individual gas boilers) to one of a more economical electricity based heating system (electric panel) is when the price of gas is increased to approximately 10.0p per kWh for standard gas or to only 6.5p per kWh for gas when measured against the energy and overall life cycle costs of the ASHP system.

Table 36 Energy costs per kWh for two scenarios compared to the base case.

	Units	Base case	Scenario 1 (higher gas price)	Scenario 2 (higher electric price)
Electricity – standard	£ per kWh	0.131	0.131	0.262
Electricity – economy 7 day	£ per kWh	0.147	0.147	0.294
Electricity – economy 7 night	£ per kWh	0.074	0.074	0.148
Electricity – business	£ per kWh	0.106	0.106	0.212
Gas – domestic	£ per kWh	0.041	0.082	0.041
Gas – business	£ per kWh	0.028	0.055	0.028

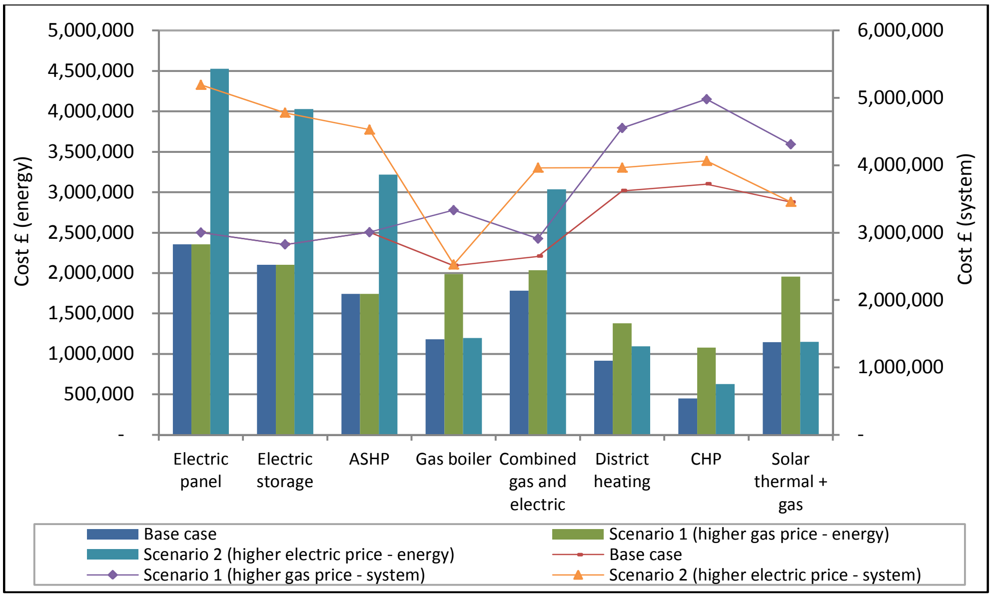


Figure 111 Impact on system and energy cost with changes to the unit price of gas and electricity.

[Overall costs for electric systems become lower with decreasing electric unit prices].

5.4.2 Construction and energy costs

Construction costs shown in the study include the replacement of equipment and components during the 40 years. When construction cost and fuel cost are compared respectively across the eight heat systems, the difference between the two is smallest for the gas boiler system -£550,000 and greatest for the electric panel system -£1,820,000 at 0% discounting rate. However, the solar thermal and gas system, district heating, and CHP represent a positive difference (fuel less cost than construction), with the former the smallest +£200,000 and the largest, the latter at +£958,000. The system with the lowest construction and energy costs remains the individual gas boiler. Systems that are possibly more adaptable to changes in fuel and are less vulnerable to specific changes in fuel cost are the district heating and CHP systems. Comparing the systems using a 5%

discount rate gives a narrowing of differences between construction and fuel cost over the range of systems, nevertheless the ranking of systems remains the same.

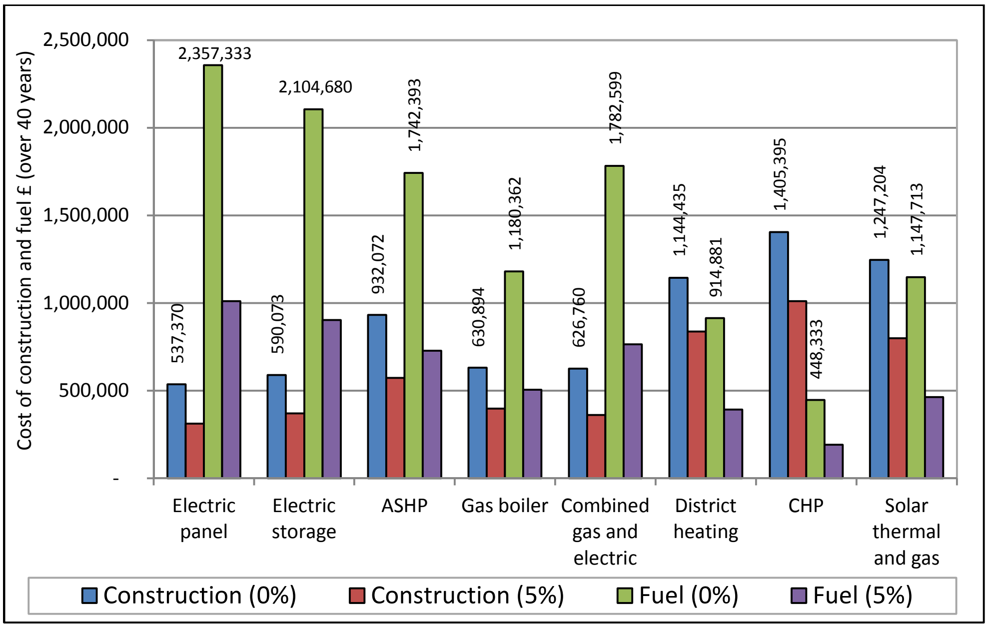


Figure 112 Comparison of construction and replacement cost against cost of fuel used.

5.5 Summary

The sustainability results for the life cycle cost impacts of the eight heat providing systems can be summarised as follows:

- Of the eight systems investigated, the use of the individual gas boiler system for space heating, water heating and cooking is the least costly at £2,510,400 over 40 years. The LCC of the gas boiler is predominately due to the lower cost of fuel gas £984,022. However, the gas boiler system has considerable life cycle maintenance and servicing costs at 25% of the overall life cycle costs.
- Of the all-electric systems the electric panel was the most costly £3,001,811 due to its use of standard electricity rate for all types of heat demand.
- A close match in life cycle costs exists between the gas boiler £2,510,400, combined gas and electric £2,648,929, electric storage heater £2,824,159, and ASHP £3,007,406 over the 40 year study period. This is essentially through the consumption of cheaper gas for the first two systems and the use of off-peak and commercial rate electricity for the latter systems respectively.
- The CHP and district heating systems are the most costly overall £3,702,119 and £3,606,472 respectively owing to the high initial construction costs and the level of on-going system repair and maintenance.
- Equipment and components that incur the highest life cycle percentage cost for systems include:
  - *Energy convertors* – Gas boilers (8%), storage heaters (8%), solar thermal panels (7.2%), ASHP units (7.1%), electric panels (7%)
  - *Heat stations* – District heating (6.2%), CHP (6%).
  - *Hot water distribution networks* - District heating (5.4%), CHP (5.3%),
  - *Wet apartment heating systems* – Gas boiler (5%), ASHP (4.3%)
  - *Common hot water pipework* – Combined gas and electric (4%), ASHP (3.5%),
  - *Storage cylinders* – Electric storage (3.7%, Electric panel (3.5%).
- Initial construction costs (as incurred by the developer) are lowest for electric systems and highest for the community CHP and district heating systems,

whereas, operational energy costs (as incurred by the user) are lowest for the CHP system.

- Changes in energy supply prices are important; higher gas prices compared to electricity favour the electric systems making the electric storage system the least costly overall. Gas prices would need to increase (30%) every five years for all-electric systems to closely match the energy costs of the gas boiler system. For the ASHP system (most efficient all-electric system) to become as equal in life cycle costs to the gas boiler the cost of gas would need to increase to above 6.5 p/kWh with electric prices remaining as per the base case.
- All eight systems are commonly found within city apartment blocks with the centralised space and hot water heating systems growing in popularity. The results, however, ignore the impacts of household behaviour that can result in large swings in consumption and subsequent operational costs. In addition, the ratio between space heating and water heating energy use at household level can again alter costs depending on behaviour and system efficiency; this is particularly evident where two separate heating systems are employed.

The life cycle costs have been identified and the economic sustainability of each heat-providing system determined including the identification of cost improvement opportunities. The following chapter considers the social sustainability of heat-providing systems and the sustainability of the electrification of heat from two perspectives.

6. Evaluation of social sustainability using stakeholder interviews

Studies from several countries have demonstrated the technical impacts of using gas and electricity for heating in homes including Leidl and David Lubitz (2009), Henderson and Young (2008); and Cockroft and Kelly (2006). However, few studies have considered the social sustainability of existing and future heating technologies and systems in the context of urban housing. This research focuses on this aspect and considers social sustainability of electrification of heat from two perspectives - that of apartment occupants and that of other energy organisation stakeholders.

6.1 Goal and scope definition

The aim of this research component is to establish the current and future socio-economic impacts of electrification of heat in urban housing on a range of stakeholders by looking through the lens of different stakeholders and considering the reasons for the perceived trend and the factors behind its possible continuation. The specific objectives are:

- To identify the stakeholders and decision makers for energy provision;
- To determine the key reasons behind the electrification of heat;
- To identify socio-economic impacts of the current and future use of electricity for heat provision to stakeholders and decision makers;
- To determine user attitudes towards: i) electric heating; ii) alternative energy systems; and
- Outline the ‘grounded theory’ of the electrification of heat.

6.2 Methodology

To elicit views on electrification of heat, a methodology outlined in Figure 113 has been developed, involving online surveys and face-to-face interviews of different stakeholders and decision makers. First a pilot questionnaire was developed and occupants of the apartment blocks previously described in Chapter 3 were surveyed. This served to inform development of a full questionnaire which was then used for online surveys of apartment occupants across England. In parallel, face-to-face interviews were carried out of decision makers in organisations involved with the heating technologies. Both occupant and organisation surveys cover a limited but relevant number of stakeholders. The following sections describe each type of survey in more detail.

6.3 Survey of apartment occupants

6.3.1 Pilot survey

During the pilot stage, 54 households were interviewed across five apartment blocks and four different heating system types identified - see Table 37. Semi-structured questionnaires and interviews were used for these purposes - see 19 Appendix 9 for the interview questions. The purpose of this survey was to obtain a technical overview of the apartments and buildings and help to fine-tune questions for the main survey of occupants across England.

The questionnaire consisted of five main sections:

1) *Background information* – apartment type, owned or rented, number of bedrooms, age range of occupants;
2) *Heating system* – type of heat system installed, renewable energy systems available and building insulation standard;
3) *Heat tariff* – basic energy tariffs, system maintenance and approximate costs per annum;
4) *Qualitative questions* – heating system effectiveness, positive and negative aspects of system, system preferences and changes, renewable energy technologies relevant for apartment block, household energy saving strategy, vision of future energy supplies in UK; and
5) *Instant reaction questions* – motivation for heating system types, 'all electric' barriers and community energy supplies.

An overview of the pilot survey findings is given in Table 38 and a summary of responses shown in 19 Appendix 9. Each of the survey apartment blocks has the same heating system technologies throughout their block – the only variations were where apartments had more bedrooms or required extra hot water storage capacity. Specific responses from occupants of each block are now discussed:

- *Emmeline* – the majority of occupants were single and young – generally between 18 and 34 years and on the whole rented their apartments – they are highly mobile and likely to move within two years. Apartments were occupied only in the evenings and early morning. The ‘all-electric’ systems served their lifestyles well – the instant heat from panel electric heaters and hot water storage using electric immersion heaters and electric cooking. The higher electric costs were a concern but this was not considered as a major issue as the apartments were of a high insulation standard and heaters generally used less often.
- *Christbel/Sylvia* – the apartment blocks are served by a combined gas and electric heat system. The common gas system heats water centrally for distribution to each apartment for washing and showering purposes. The electric system uses electric panels and electric cooking. The combined system serves households well with plentiful hot water and warm apartments. Concerns focused on the charges made by the energy service company (ESCo) that controls the hot water, electricity and cold water supplies. Households had no other options for energy services but relied on the residents association to influence costs through discussions with the ESCo. On the whole, occupants were more settled and likely to stay longer.
- *Roach Court* – this apartment block uses gas for heat through individual boilers and cookers; households are very pro-gas for space and water heating. Poor insulation throughout the block and a tendency to stay at home during the day results in high energy bills. Improvements in insulation were mentioned most often. Occupants are long term residents.
- *Thomas Court* - – this apartment block uses electricity for heat through modern storage heaters and well insulated hot water cylinders. The block had been recently upgraded through external insulation, cladding and double glazing throughout. Householders struggle with the planning and organising of electric heating especially the timing of the storage heaters – respondents wanted to see the heaters changed or improved. Occupants are a mixture of long and short term residents.

Responses for the three pilot survey instant reaction questions are shown in Figure 114, Figure 115, and Figure 116. Cost dominates the responses with occupants looking to save on bills presently and expressing concern at the possible future cost of electricity.

However, there is recognition that heat providing systems should be better for the environment, reduce pollution at power stations and use renewable technologies. Occupants expressed their concern on community based systems especially the loss of control and the involvement of companies who may be used to manage the system.

The pilot survey provided background technical information and data on different apartment blocks and the general views of occupants toward their heat provision. The survey approach – through door to door questioning was slow and time consuming however within each apartment block, occupants' responses to questions were relatively consistent. Overall, the pilot interviews conducted suggested that occupants' attitudes to the electrification of heat varied according to socio-demographics.

Based on occupants' feedback, the pilot survey questions proved realistic and answerable however questionnaire fatigue was a common occurrence. Residents associations proved difficult to access for surveys for several apartment blocks and therefore this stakeholder was mainly disregarded for the wider survey. The format of the survey was subsequently changed although the questions remained essentially the same – this is discussed further in the next section.

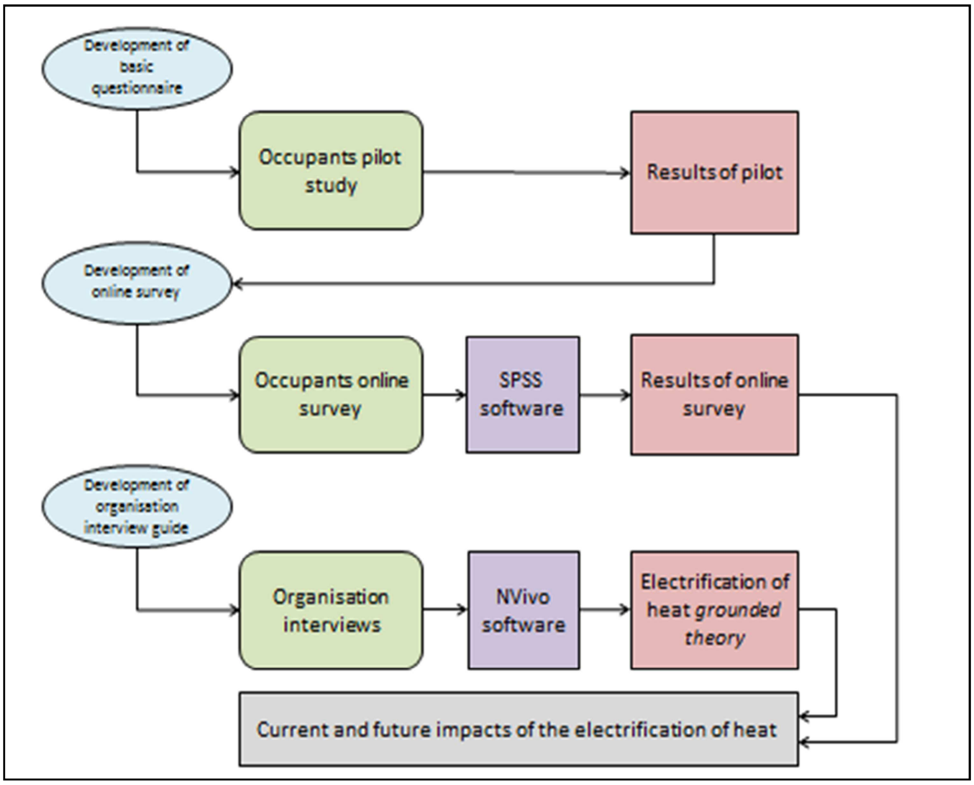


Figure 113 Boundaries and approach to assessing the social sustainability of electrification of heat.

Table 37 Face-to-face interviews of occupants during the pilot survey.

Apartment block	**Number of apartments**	**Number of households interviewed**	**% interviewed from total number apartments**
Emmeline	62	9	15%
Roach Court	62	10	16%
Christabel/Sylvia	124	30	24%
Thomas Court	50	5	10%
Total:	**298**	**54**	**Overall % interviewed: 18%**

Table 38 Pilot survey overview.

Apartment block	Heating system	Predominant resident group	Focal comments
Emmeline (private rented or owned)	Electric panel	Young, student, professional (78% are single occupants and mobile[1])	Concerned about expenditure on electricity but felt they could control and manage energy consumption and overall costs to suit their lifestyles and budgets.
Christabel/Sylvia (private)	Combined	Young/middle age professional, some families (77% are single occupants)	Apprehensive about charges and felt there was a lack of available options to change or challenge their energy provider to reduce costs.
Roach Court (local authority allocated housing, few private)	Gas boiler	Older and retired people (70% of households have two or more occupants).	Hesitant about fuel costs, possibly reflecting lower incomes and the tendency toward the apartment being occupied for more hours per day than other blocks. Very concerned about inefficient homes and systems but pro-gas.
Thomas Court (local authority allocated housing)	Electric storage	Middle age/older retired and asylum seekers.	Recent building improvements to insulation have improved energy efficiency. New all-electric heat does not suit households.

[1] Likely to move within two years.

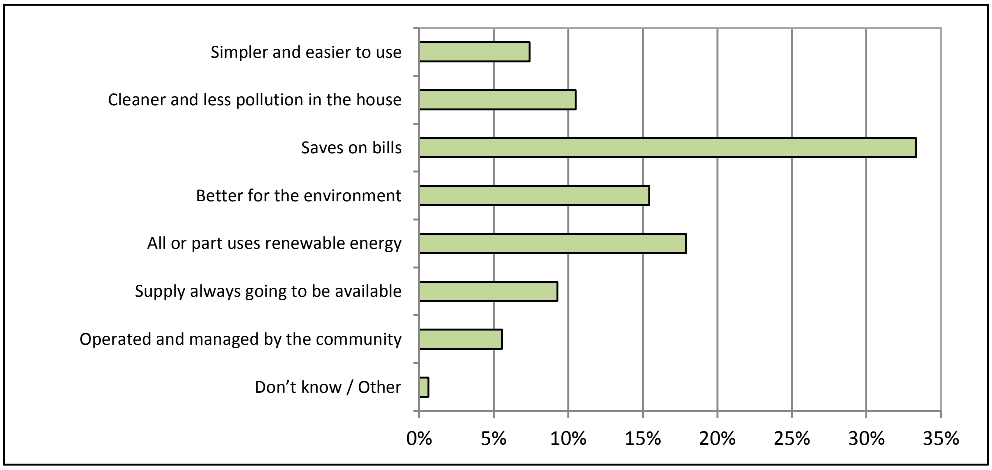


Figure 114 Factors that occupants would like to see from their current and future energy supply.

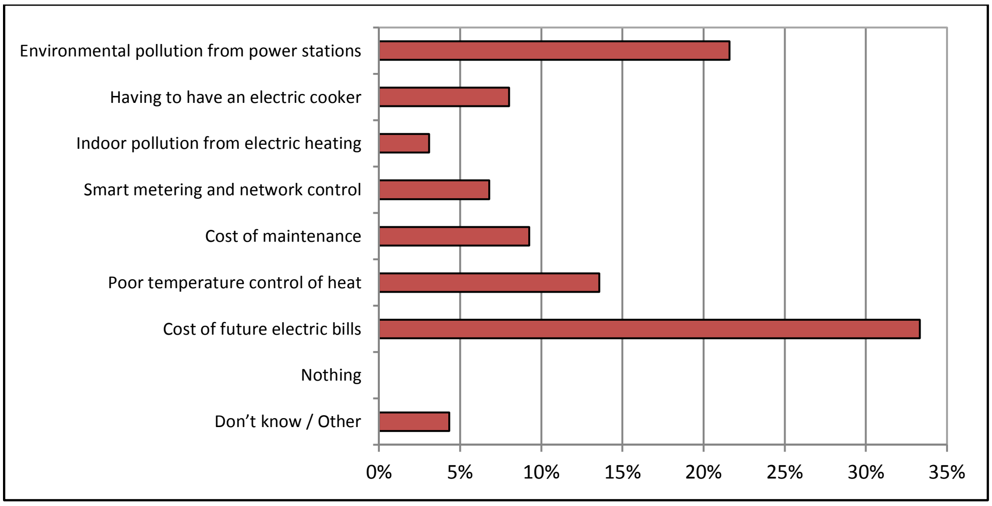


Figure 115 Factors that concern occupants about living in an apartment where both the heating and hot water come from electricity.

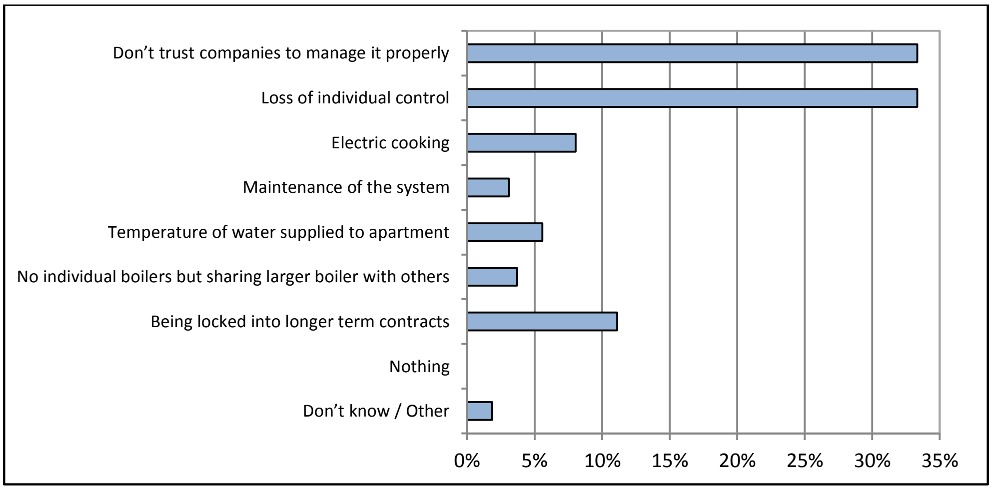


Figure 116 Factors of concern to occupants if their energy supply is or could be turned over completely to a community supplied system.

6.3.2 Main online survey

The online survey consisted of 40 questions covering the areas shown in Figure 117; the full questionnaire can be found in 19 Appendix 9. The questionnaire was developed based on the experience gained from the pilot survey and the University proviso that an online questionnaire approach be used for the study.

The online questionnaire was built using *Qualtrics* research software (Qualtrics, 2011) through the University of Manchester Business School and web access for the online data collection. Qualtrics provides the platform for the questionnaire and receives and saves the responses ready for analysis and reporting within Qualtrics itself or as in this study for use in SPSS (IBM, 2013). SPSS was used to conduct descriptive statistics on the data using the frequencies, crosstabs and descriptive functions.

The questionnaire was promoted via the internet, including The University of Manchester volunteer website, apartment residents associations, energy conservation organisations and PUrE Intrawise website. In total, (175) households had completed fully the online survey with the majority of respondents located in Manchester - see Table 39. On completion of the online questionnaire participants were asked if they would be willing to take part in a telephone interview based on the replies given in their questionnaire – this was conducted by ten participants.

The online questionnaire and study asks questions particularly of people who live in apartment blocks where there are common energy supplies (electricity, gas or heat) to each household. They consider the way energy services such as gas and electricity are delivered to homes and how they are used for home heating, water heating, and cooking. The questions refer throughout to ‘modal switching’ however this was explained in the context of the electrification of heat or an all-electric approach.

The questionnaire starts with an introduction and explanation to the participant of both the question process and the research – this is facilitated through the participant information form. Diagrams and supporting information assist in clarifying the extent and requirements of the research. The questions were formulated to gather data on the:

- Current heating and cooking systems;
- The use of electricity for all households needs – heating, cooling and cooking;
- The implications of using alternative energy supplies and technologies; and
- Any social and economic implications of changes in city energy supply and its use.

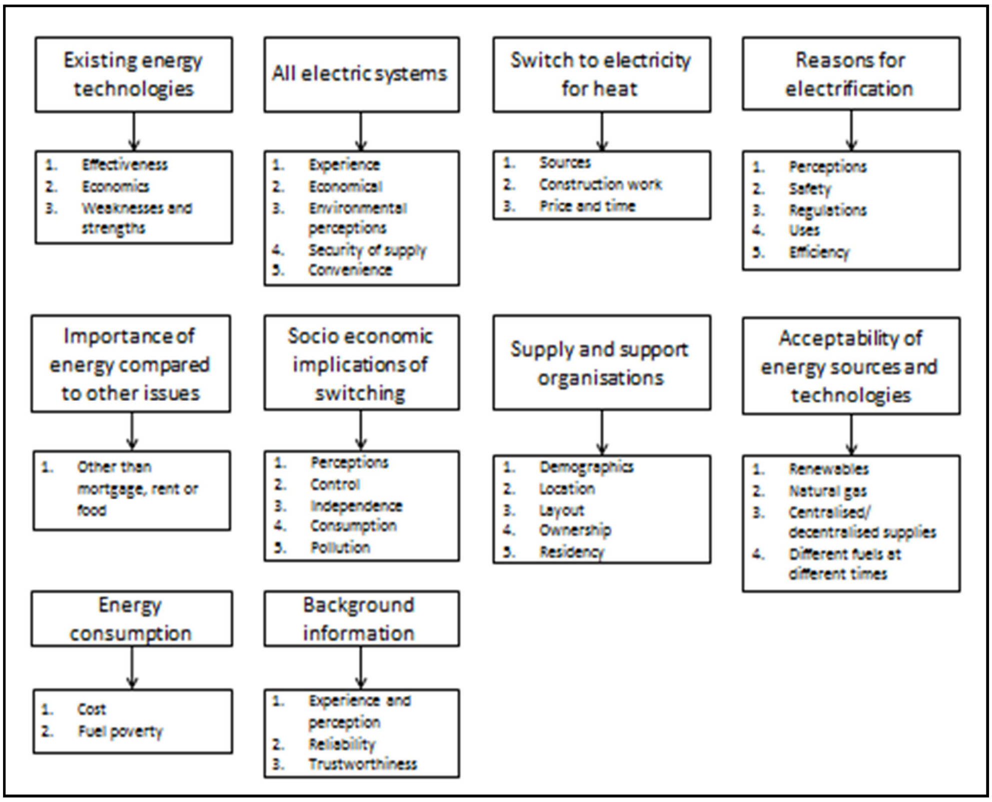


Figure 117 Overview of the content of the online questionnaire.

Table 39 Online questionnaire completed and occupants' locations.

Approximate location of respondent	Number of occupants commencing survey	Number of occupants completing survey
Manchester	190	134
Leeds	1	1
Liverpool	1	1
Oxford	1	1
London	4	4
Brighton	5	5
Sheffield	12	12
Newcastle	17	17
Total:	***231***	***175 (76%)***

6.3.3 Online survey results

Each question or group of questions are now described providing background information to the question, the responses from participants and how the results are used in formulating indicators that are used subsequently in the Multi-criteria decision analysis Chapter 7, and the Scenario analysis Chapter 8.

Questions 1 – 2: provides a perspective as to why the householder is currently living in the particular property and to determine if the heating system installed was a deciding factor in the decision to live there. Results show that the type of heat-providing system installed in the home had limited influence 8% as a factor for the occupants to select that property; instead, purchase or rent price 59%, location 54%, and transport connections 37% had the greatest influence. This is understandable as estate agents or housing associations have not until recently made the heating systems a selling point - greater attention now given to home efficiency through energy performance certificates (EST, 2013), purveyors are now including this in their sales documentation.

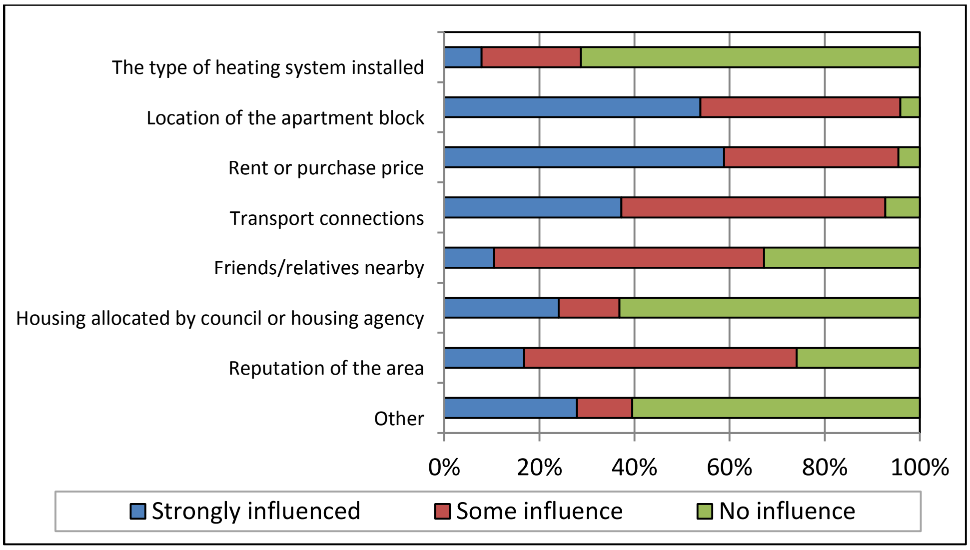


Figure 118 Factors influencing when property bought or rented.

Questions 3 – 9: provides an overview of the effectiveness, efficiencies and economics of the property's existing space heating, water heating and cooking systems and expresses this comparatively according to each heat providing technology. The questions seek a response as to whether one system (electric or other) is more efficient or economical over another and particularly concerning the sole use of electricity for heat and if the respondent has experienced this type of system currently or previously. Note question 7 is not used here as this originally explored household cooling.

From the respondents of this survey, more than 62% are living or have lived in homes heated solely by electricity. In terms of energy supplied and used, nearly 2/3^{rds} are using heat provision by electricity and 1/3rd utilizing gas – see Table 40. Occupants principally use their space heating systems in the morning and evenings or on a variable basis - fewer than 10% use them all day - Figure 119. Of those surveyed, 80% are using electric ovens and 71% electric hobs for cooking - Figure 120.

No clear picture emerges when comparing the adequacy and economics of the different heat providing systems; electricity is considered slightly more economical for space heating 39% and water heating 47% while gas provides slightly better adequacy of provision (SH - 72% and WH - 82%) – see Figure 121. Other systems, principally solar thermal, district and CHP heating are seen as less economical overall although the number of respondents in this category was very small - only (3%) of the total respondents.

Concerning the economics of electric heat, apartments generally have one or two bedrooms only and relatively small floor areas – this can enable electric heating to heat these areas quickly and economically (see Table 41 - strengths) and match the time demands of busy households whereas wet systems take time to warm and then heat the rooms and perform better over long heating durations. As observed in the pilot study, where gas heating is experienced presently or previously there is a lasting appreciation of gas heat providing systems. Analysis also shows that the larger homes (3 bedrooms+) showed a preference for gas heating.

The numerical results from these questions are combined in the technical indicator: *System effectiveness and efficiency*. The indicator reflects space and water heating, and cooking adequacy and efficiency for the eight heat systems. This indicator is used in Chapter 7 and 8 of the study and the numerical output shown in 19 Appendix 9.

Table 40 Energy used for heat provision to occupants' homes.

	Gas	Electric	Other	Don't know
Space heating	32.1%	61.6%	2.7%	3.6%
Water heating	32.1%	59.8%	0.9%	7.1%

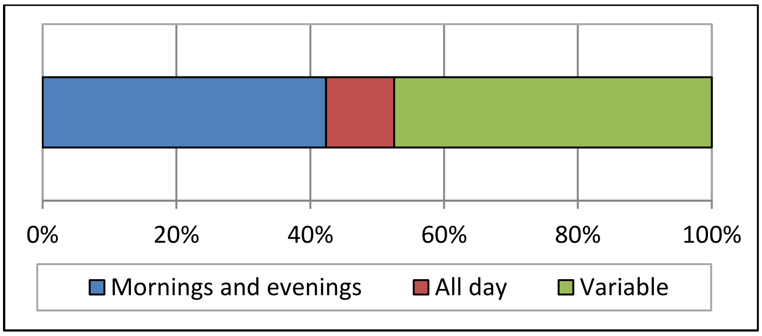


Figure 119 Times of day respondents use space heating.

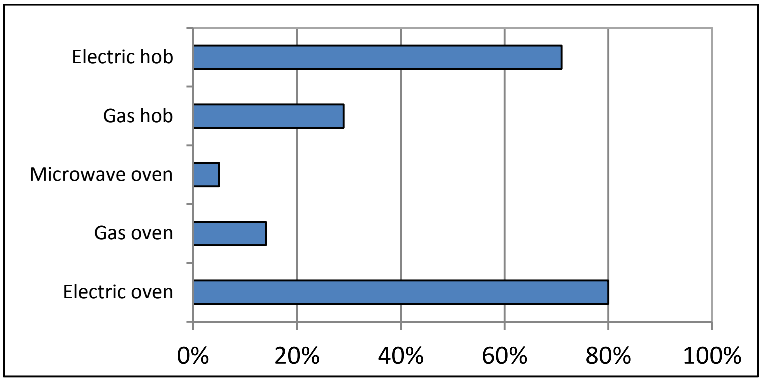


Figure 120 Type of oven and hob used.

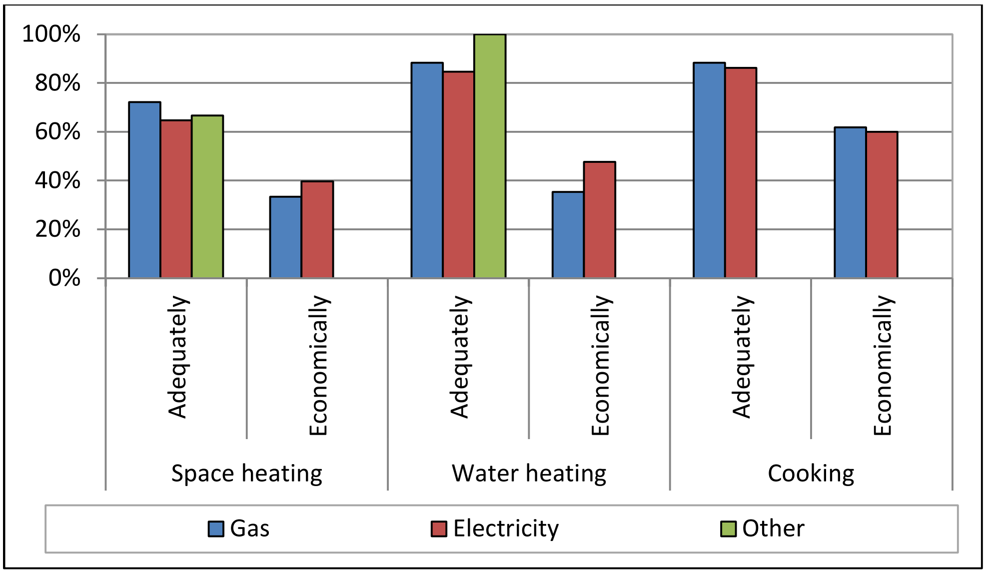


Figure 121 Comparison of adequacy and economics for heat provision systems.

[Data shown are where occupants have strongly agreed or agreed with adequacy and economically for each heat provision. Data is based on number of respondents using gas or electric etc. against total respondents using the same fuel].

Occupants have identified the strengths and weaknesses of their existing heat providing systems and technologies as summarised in Table 41. The comments provide a sample of occupant's views toward gas and particularly electric heating systems and how they are used and experienced in daily life.

Table 41 Strengths and weaknesses of heat providing systems by fuel type from occupant perspectives.

Principal heat providing fuel	Strengths	Weaknesses
Gas	Affordable, instant Combi-boiler means constant hot water as and when required Heating is there when needed and quick to turn on Can adjust and set the systems to suit household needs	Expensive during winter Slow to heat up whole house Complicated to understand Efficiency of water heating compromised Loud and noisy heating system System often has faults/breakdowns Takes up space.

	New boiler gives good efficiency Easy to configure.	
Electricity	Quick to heat Only one bill per period and easier to track expenditure Good insulated homes means low use of heating Can control heaters individually Minimal maintenance Electrics heaters can eventually heat the room space significantly Economical and efficient Fast, effective, safe Reliable, quiet, simple Uses cheaper off-peak electricity.	Very expensive to run especially if left on for long Not enough market choice for economy 10 and economy 7 not so cost effective as advertised Bulky electric heaters Electric cooking quite slow and inconvenient Storage heaters are slow to respond Expensive and largely ineffective Hot water runs out after 20 minutes Not warm enough in flat Large room is difficult to heat, heater unreactive and temperatures uncontrollable Long time for water to get hot Requires a lot of guess work Heaters can't be covered for drying purposes Difficult to track amount of hot water remaining.

Questions 10: considers the householders experience or perceptions of an all-electric energy supply. Previous experience with particular heat providing systems or perceptions about them can influence householders in the choice and use of technologies. Occupants were asked to consider the impacts of any electrification of heat from the perspectives of pollution, security of supply and cost.

As indicated in Figure 122, 64% of occupants thought that electricity produced lower indoor pollution but 56% greater external pollution through its generation. However, less than 25% said it was more economical. Nearly 47% consider electricity provides an improved security of supply and 41% suggest that an all-electric dwelling would be a home in which they personally would want to live. Further, there is no overwhelming view as to whether cooking by electric is better 23% or worse 26%. With over 62% of surveyed occupants having lived or living in all-electric homes, many have possibly experienced less indoor pollution, however whether this is due to improved air extraction or electrification of heat is not clear.

The results from this question consider the electrification of heat as providing positive aspects – reduction of internal pollution 64% and security of supply 47%. However, the response regarding electricity for heat being less economical appears to contradict with the response given in questions 3-9. Referring to (Table 41 – weaknesses), electric heat is also considered expensive and overall uneconomic. This question however refers to the bigger picture and suggests that overall electric heat is less economical than the other energy forms compared. However, for a notable number of households electric heating can be economic – and therefore the positioning of electricity for heat provision could be based on household behavioural characteristics.

The technical indicator developed from this question is: *System perceptions and experience*. This comparative indicator expresses the overview of opinions concerning system performance and intrinsic value. The numerical output from the responses for each system type is shown in 19 Appendix 9.

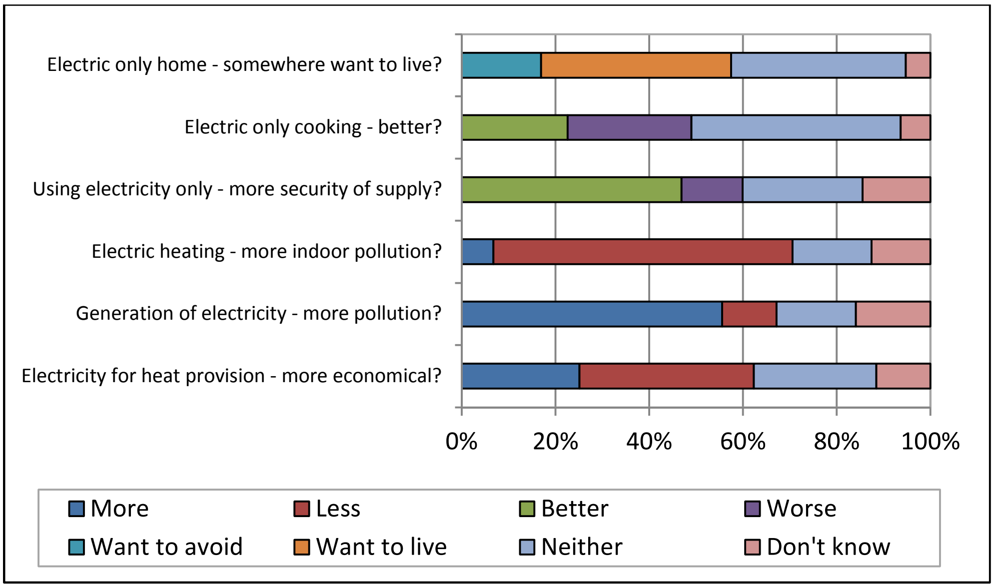


Figure 122 Responses to electrification of heat.

Question 11: considers key aspects of any future electrification of the energy supply and how acceptable this would be to householders. The question reflects on the acceptability of upstream factors to householders that may limit or enhance a technologies potential especially concerning the electrification of heat. Particular emphasis has been given to peak demand period controls that could be inherent with electric heat so as to minimise peak demands and overall power network loads. Acceptability of pollution levels from further power generation and the local generation of electricity energy from lower carbon sources are also considered.

Overall, occupants are positive toward the local generation of electricity from renewable and high-efficiency sources with 82% being in favour; however, they are sensitive (only 10% saying very acceptable) to paying more for energy during peak demand periods, but still 43% consider the issue fairly acceptable especially if there are much lower charges at other times. Additional construction work such as underfloor heating or the installation of storage tanks or heat stations within homes shows only 9% consider this very acceptable but 37% suggesting this is fairly unacceptable. Accepting the current pollution levels particularly from power generation for a further decade or more was seen as fairly and very acceptable by 37% and 14% respectively when considering the electrification of heat - see Figure 123.

Householders show positive responses to delaying pollution level improvements, the local generation of electricity and considering different prices for energy at different times. The latter suggests an opportunity to save but a requirement to lightly adapt by the householder whereas the former two could be considered as being out of the householder direct control anyway. The suggestion of additional construction work to accommodate any new heating systems is not well received and possibly relates to the 'hassle factor' – see section 6.4.

The social indicator developed from this question is: *Acceptability of upstream factors* and represents occupants' views on upstream impacts from future electrification of heat. The numerical output from the responses and their use in the indicator are shown in 19 Appendix 9**.**

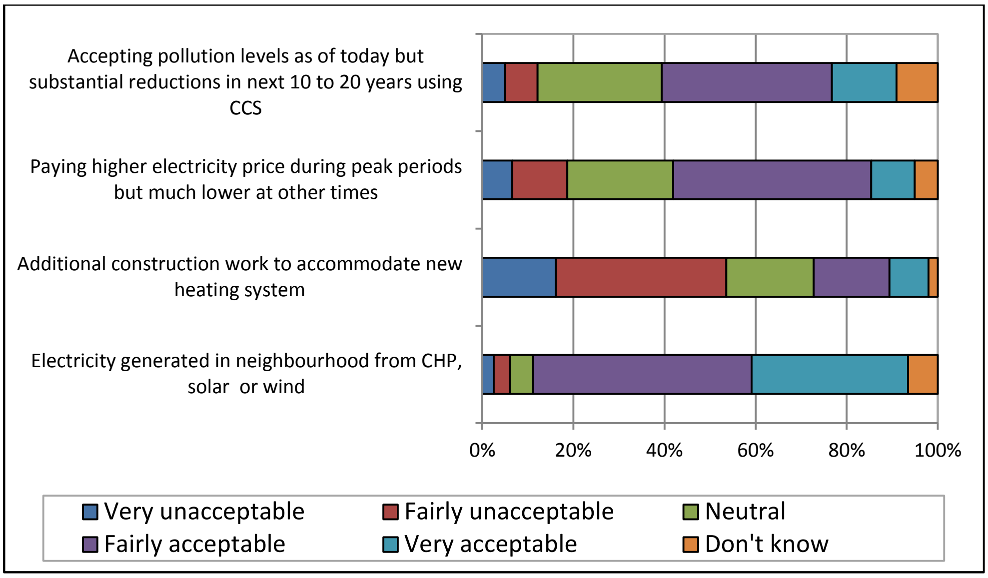


Figure 123 Acceptability of heat electrification for apartments.

Question 12: seeks to establish possible reasons for electrification of heat from the perspectives of the householder through the provision of a number of plausible explanations from which to choose. It considers the overall safety and impact of regulations on technologies and systems and the way in which practices and initiatives may restrict or promote the use of certain fuels and associated systems.

Based on occupants' comments, the electrification of heat trend has developed from a number of interventions chiefly, electricity having a wider range of uses 72% and gas safety issues 65% - see Figure 124. Occupants also recognised, but to a lesser extent, that the change from gas to electricity could have occurred due to improved building standards or initiatives such as through the use of insulation 56% and the actions of developers in installing electric only systems in buildings 55%. However, only 40% suggest that building regulations can restrict the use of certain fuels with buildings.

The question criteria and their numerical responses are combined in the technical indicator: *Safety, regulations and uses*. The indicator reflects on the range of reasons concerning heat electrification and applies these to each of the heat providing systems studied. Specific details are shown in 19 Appendix 9.

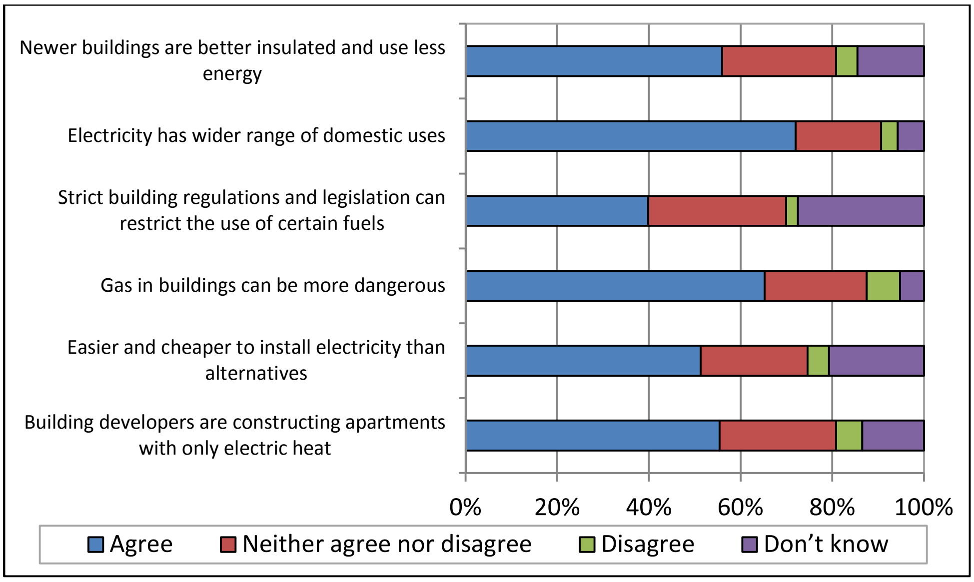


Figure 124 Change from gas to electricity.

Question 13: considers the importance of energy to householders when compared to other issues to determine a sense of the value of energy within a range of issues. In terms of expenditure and priorities, (other than mortgage, rent or food), respondents suggested transport costs 24%, and telephone, broadband and water 14% as their other key concerns rather than energy 12% – see Figure 125. 'Others' refers to a combination of smaller priorities including leisure activities, socialising and holidays. The results suggest a moderate level of importance placed on energy as a household cost nevertheless, given the average age of respondent (below 34 yrs.), the priorities stated need to be seen in the context of questions 24 – 30.

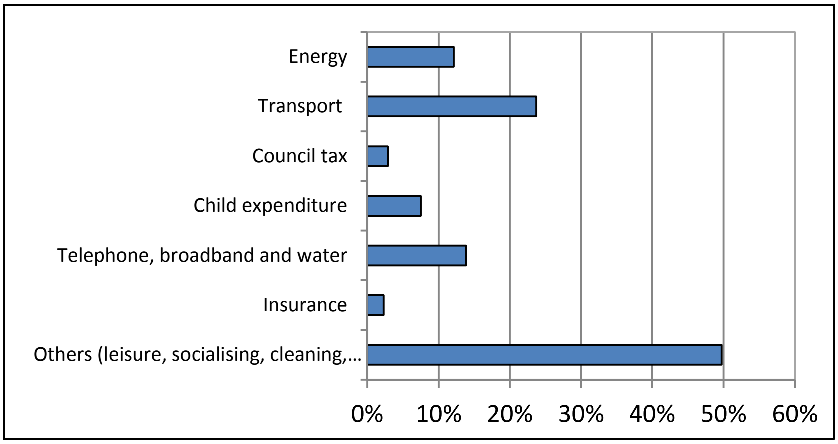


Figure 125 Key household expenditure.

Question 14: in the future, apartment blocks and flats could use various sources of energy and technologies – the proximity and acceptability of these was assessed from the householders perspectives. This is a measure of the inclusive ability of the technology or system to use renewable technologies or energy and includes the capability of energy use at variable times during a day. The participant information form explained the background to 'emission shifting' - as it is referred to and briefly described the technology options – See 19 Appendix 9.

The responses are listed in Figure 126. On the whole, the replies were positive with very acceptable for solar thermal and solar PV panels on apartment roof tops 60% and 57% respectively, and district heating at 52%. Lower acceptability's were obtained for biomass boilers 26% and energy from burning waste 24%. Awareness of each of the technologies was high at 94.5%.

Occupants were also asked if using different energy types at different times (gas, electricity or district heating for heat) would be acceptable – more than 48% suggested this was acceptable. This is important as future energy scenarios suggest the use of multi-energy sources to facilitate supply challenges (Brooke, 2010).

The technical indicator developed from this question is: *Heat technologies and energy sources*. The indicator shows how each of the heat providing systems is assessed against the opportunity of renewable technology and system link in. The numerical output from the responses for this indicator is shown in 19 Appendix 9.

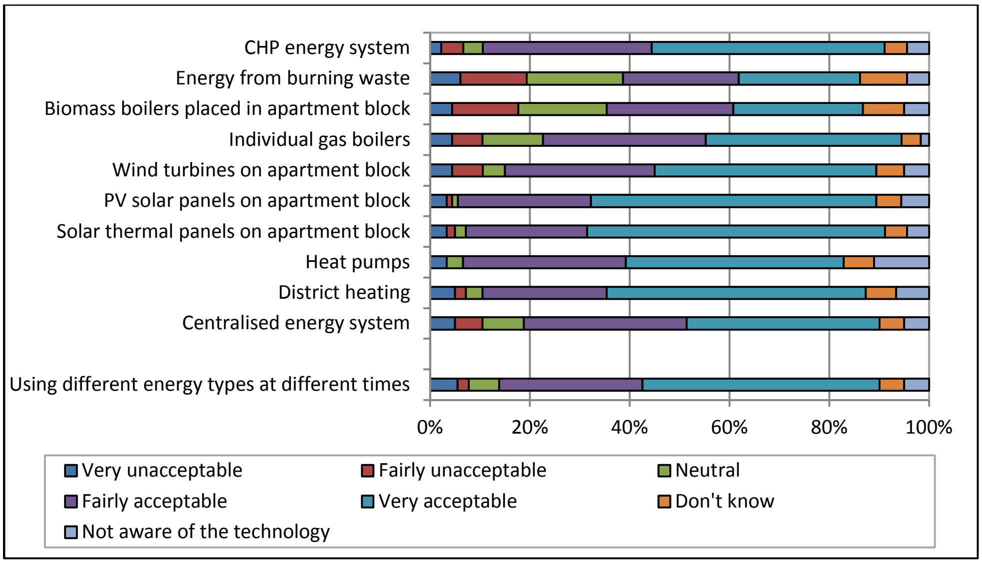


Figure 126 Acceptability of various sources of energy and technologies.

Question 15: considers the socio-economic implications of the electrification of heat for city householders including heat control and management as a measure of how much control householders have over their energy supply and how it is managed through its provision and use.

Occupants view positively initiatives such as smart meters 76%, localised power generation 72%, and control over who supplies electricity 79%, short supply contracts 58%; less positive is pollution shifting from homes to power stations 34%.

Householders like to have control over their energy expenditure and the ways in which this can assist are seen as positive – improved controls, shorter contracts and locally generated power. Apartment occupants are often tied to a service company or supplier especially where common heat systems are provided – householders want greater control on who supplies their electricity providing an improved range of tariffs and opportunities. Concerning pollution, although householders are not positive toward shifting, the responses are overall neutral suggesting this aspect is fairly balanced and understood by occupants.

The technical indicator developed from this question is: *Heat control and management* and represents the extent of heat system impacts related to control and management. The numerical output from the responses is shown in 19 Appendix 9.

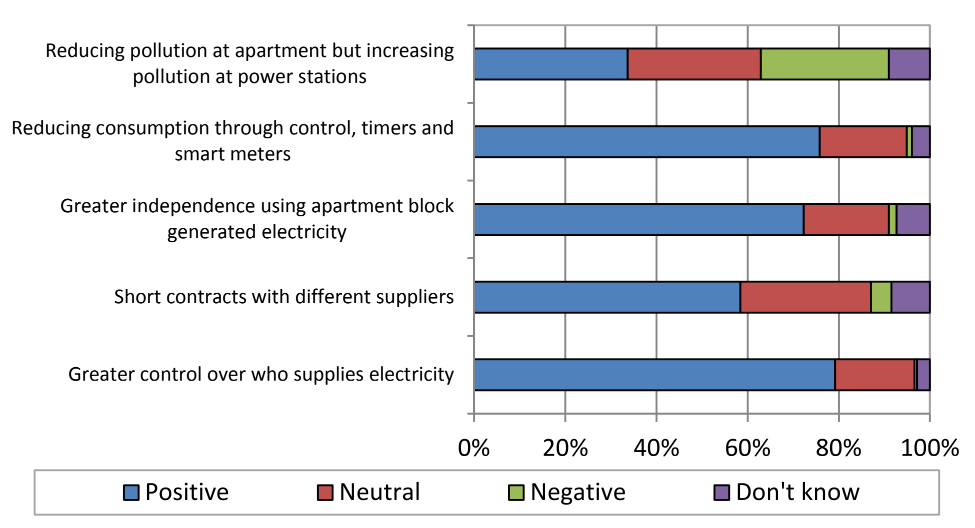


Figure 127 Acceptability of possible all-electric impacts.

Question 16: looks at which organisations householders consider most appropriate to organise community energy supply schemes. Occupants were asked to identify organisations that they most trust to provide and manage energy supply systems for apartment blocks and communities. As indicated in Figure 128, those most trusted include: local authorities 59%, national government 34% and cooperatives 33%; least trusted are private energy management companies 6% and utilities 14%.

Where common heating systems are concerned, householders appear to seek organisations that are accountable and fair and are not seen as being exploitative, hence the high score for the local authorities. In addition, many of the survey respondents live in cities where there are existing local authority heating schemes operating and therefore may have exeprieced these first hand. Occupants' surveyed mentioned they wanted to keep control of their energy and deal directly with the larger fuel supply companies where there were opportunities to shop around. Residents associations as a trusted body are placed low in the overall list at 23%, this survey found disharmony in several residents associations concerning issues other than energy and notes that this particular question may also reflect other underlying issues.

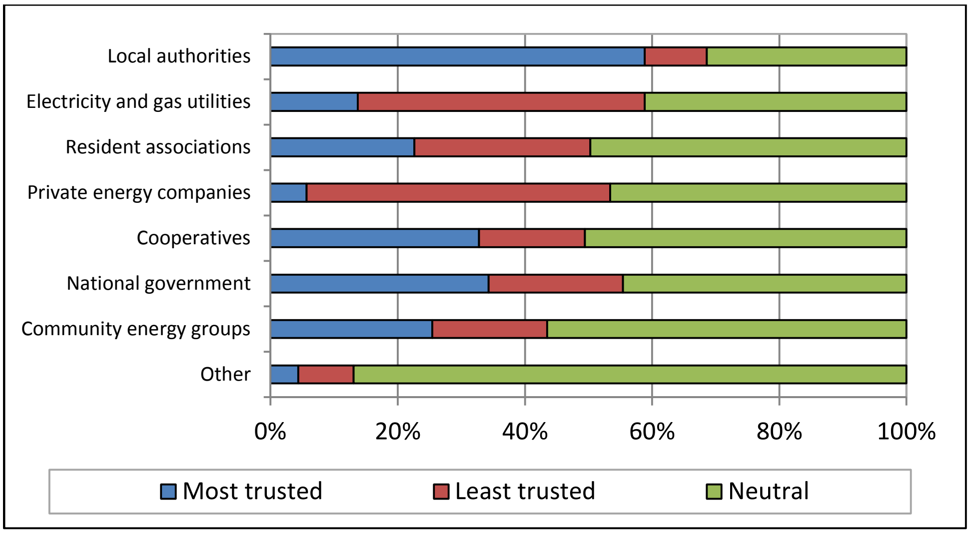


Figure 128 Organisations trusted by occupants to manage and maintain a community energy system in apartment blocks.

Questions 17 – 23: considers the basic layout of the householder's apartment and the type of cooking technologies used. This is conducted to obtain a snapshot of the respondent's home and its comparative size and features. The majority of homes responding either have one or two bedrooms 29% and 69% respectively (Figure 130). The layouts of surveyed homes are generally combined sitting, dining and kitchen 46% or have separate rooms for each 31%. The cooking element of the questions was described previously in questions 3 – 9.

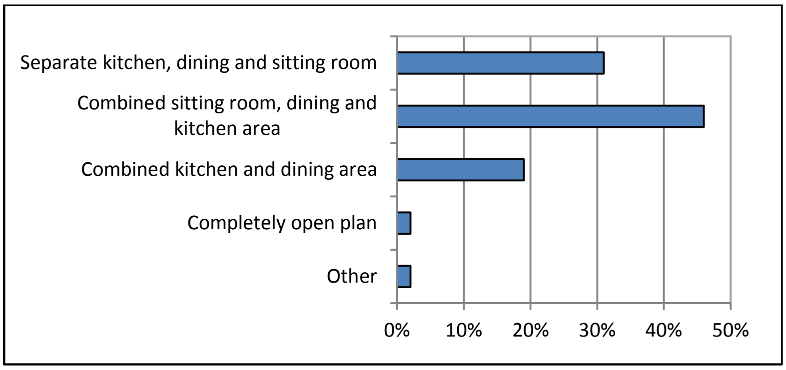


Figure 129 Floor layout of occupants' properties.

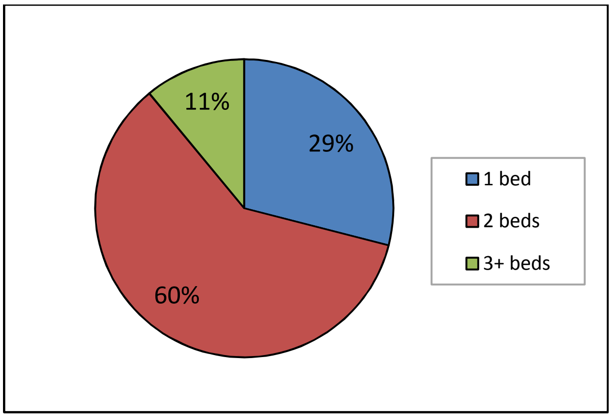


Figure 130 Number of bedrooms within occupant's properties.

Questions 24 – 30: considers householders energy bills and the type of energy tariff they were using. This provides an indication of energy expenditure and whether they are classified as fuel poor or not. Householders were also asked about their ownership of other major electrical goods and the reliability of heat related household technologies – this was to determine if further expenditure was required in addition to the fuel to operate the heat system. Washing machines and fridge freezers are common appliances using electricity in the surveyed households. The reliability of heat technologies is high with an average of 11% breakdown over a two year period. Electronic heating controls are the most unreliable and both gas boilers and electric heaters offering the same level of overall reliability at more than 90% - see Figure 131.

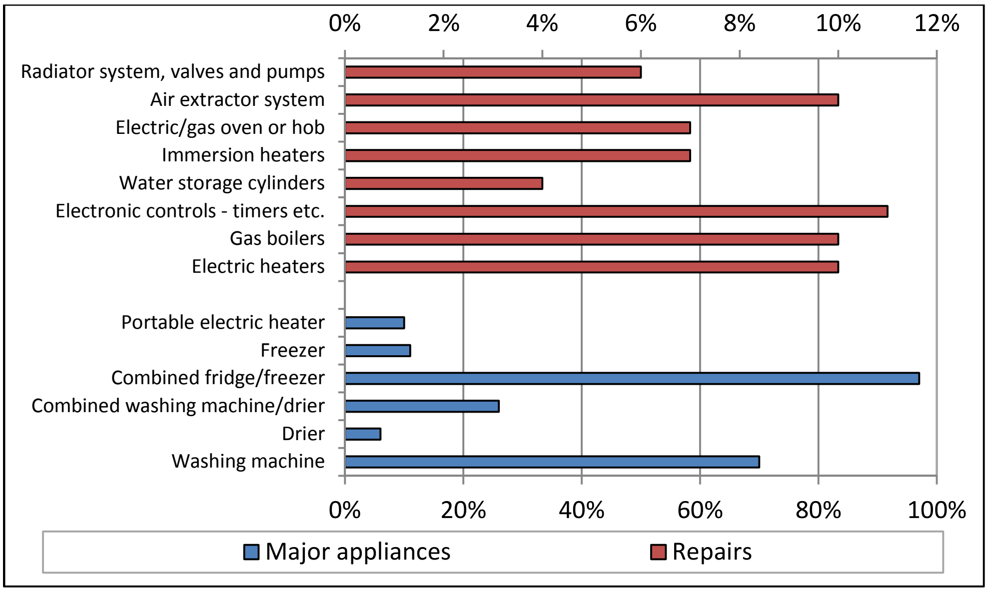


Figure 131 Comparison of major appliances found within surveyed households and repairs conducted to heat providing systems.

[Major appliances show % of homes owning or using items and represented on lower axis. Repairs are based on number of households who required repairs during a two year period and shown on top axis].

The cost of energy was highlighted by occupants as an area of concern and this is reflected throughout the survey. The majority of respondents use standard rate electricity with only 23% benefiting from cheaper economy rate electricity – see Figure 132. In apartments, it is common that only where storage heaters are used is economy rate electricity systems and metering installed. However, there are cases where the cheaper rate electricity is made available for electric water heating only.

Occupants were asked to estimate their expenditure on their fuel over a recent 12 month period when considering the type of fuels that are used within their household. Overall, electricity-only users were spending more on their energy with 40% paying between £501 and £1,000 per year compared to only 25% for gas – see Figure 133. From those surveyed, 12% suggest that they are expending more than 10% of their income on fuel over a year (Figure 134); this is evident for both electricity and gas users. Therefore, according to the Government definition (EnergyUK, 2013), 12% of the people surveyed are subject to fuel poverty.

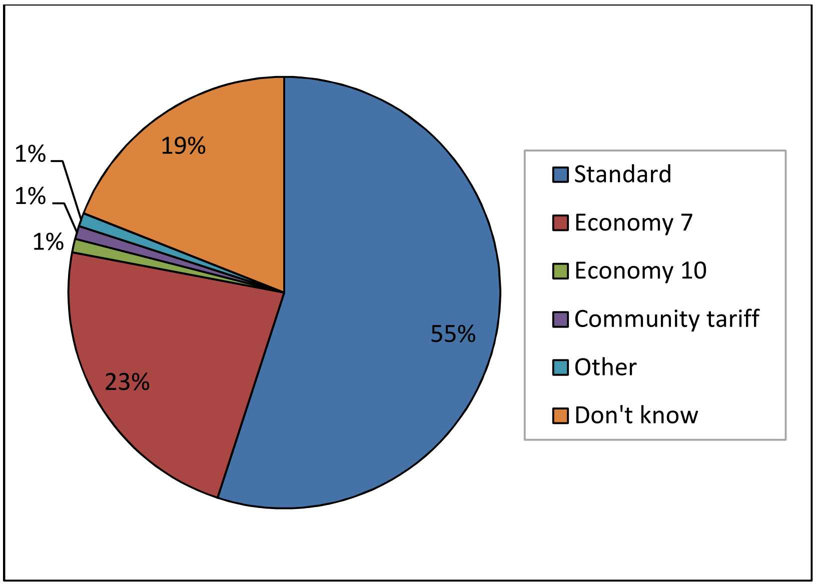


Figure 132 Broad electricity tariffs used by occupants.

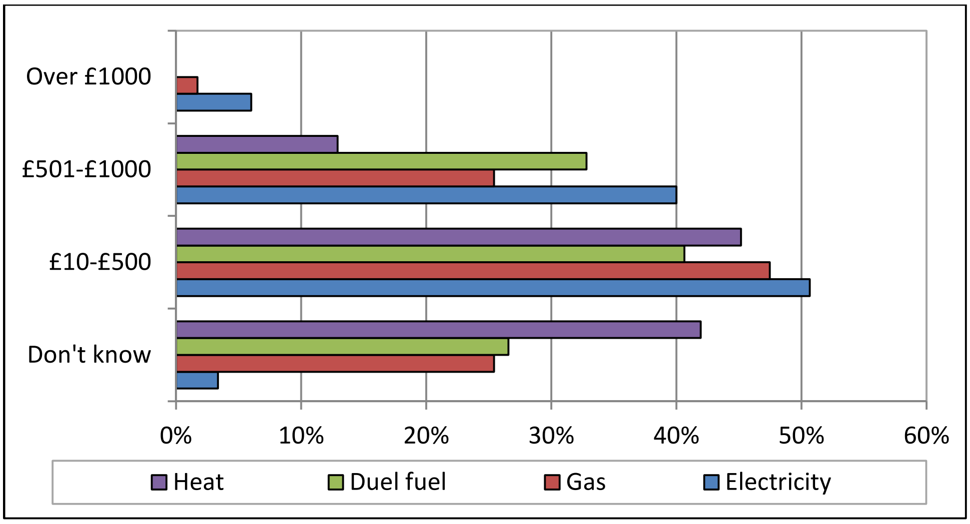


Figure 133 Occupants' estimated expenditure on fuels over a 12 month period according principal fuel type used i.e. gas, electricity.

[Survey was conducted between 2011 and 2012 and so values represent expenditure during that period].

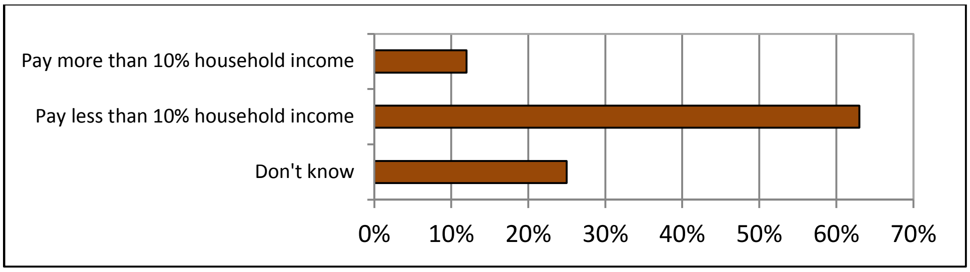


Figure 134 Household fuel poverty indication.

[Households who pay more than 10% of their income on fuel are considered to be in fuel poverty].

Questions 26 and 27 considered the location of the householders electric and gas meters. This was included as a proxy indicator of the householder level of awareness of their existing local energy supply system and metering by which they are charged. For electricity, householders showed 66% were aware of their system while approximately 32% suggested they did not know the location of their meters – see Figure 135.

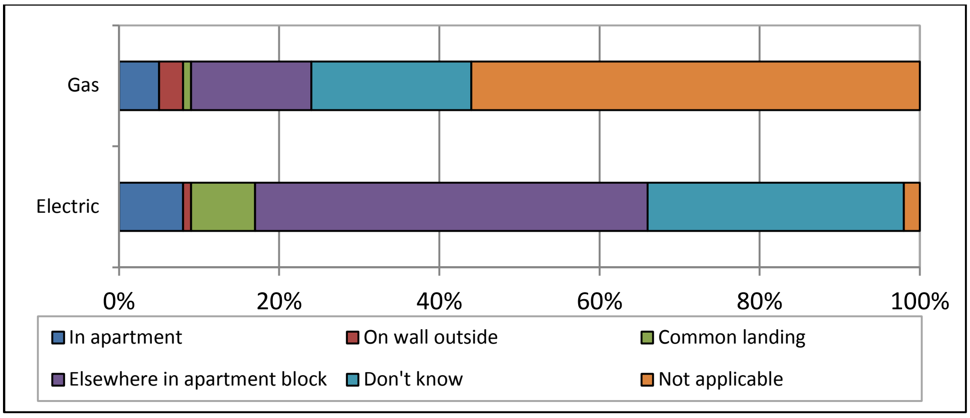


Figure 135 Location of electricity and gas meters.

Questions 31 – 37: asks about demographic details. There was a (48%/52%) response to the questionnaire from females and males, respectively, with the majority aged between 16 and 34 years – see Figure 136, and an average of two people living in the property. Occupants lived between 1 to 2 years in the property with those staying 3 years or more representing only 31% of overall respondents. 44% are privately rented and more than 40% belong to the local authority and housing associations – see Figure 137.

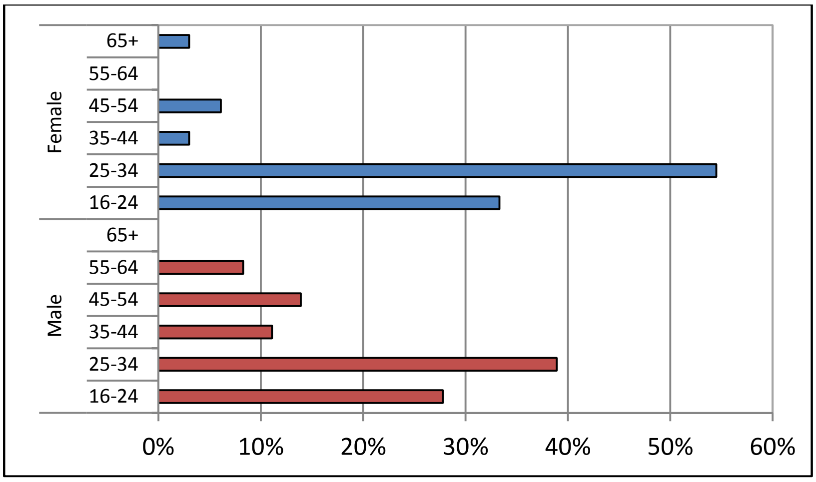


Figure 136 Demographic details of respondents.

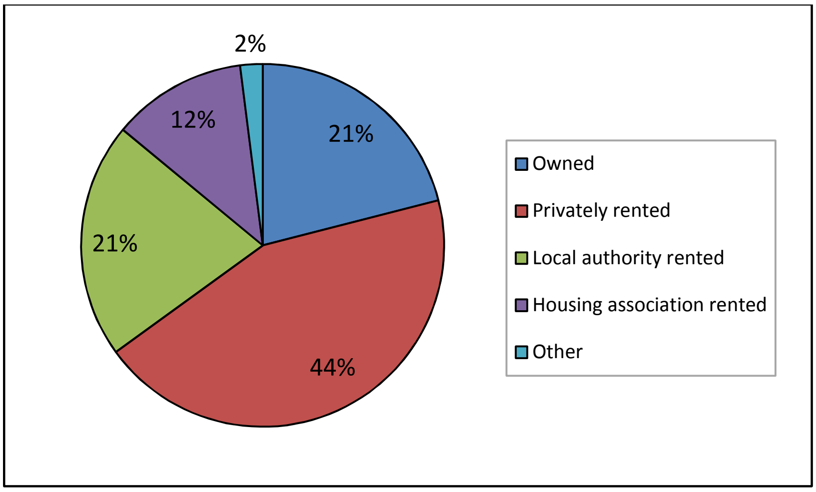


Figure 137 Ownership or rental staus of apartment.

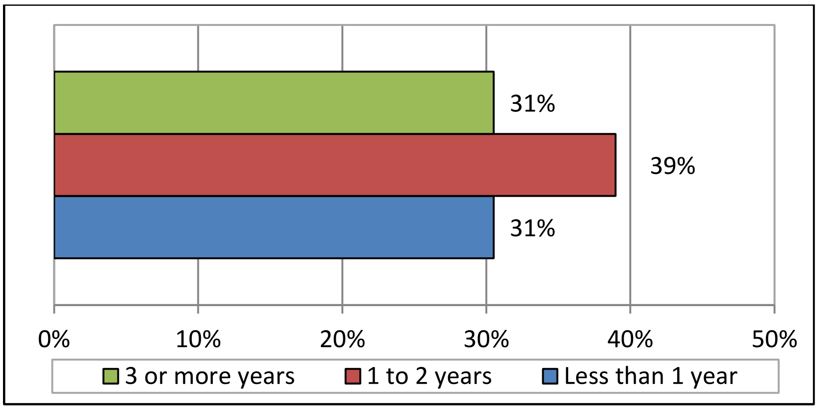


Figure 138 Years lived in the apartment.

Questions 38 – 40: these are administrative questions requesting information including: postcode, interest in any follow-up interviews and contact details.

6.3.4 Discussion of the findings of the online survey

In this survey, the majority of occupants chose where they wanted to live being either private renters or owners of the properties; however, approximately (33% - 37%) were allocated their housing so had little or no say in choosing their residence - these people would generally be lower income householders. The heating system in the home is not an influencing factor in choosing to live there or the energy efficiency of an apartment or house.

Comparing system performance as seen by the occupants shows that generally they consider that their heat-providing system provides adequately for their space heating, and more so for their water heating needs. There is little difference between effectiveness and economics of either the gas or the electric heat systems. However, householders identified the strengths and weakness of both systems but these were found to apply equally to both and overall could relate to householder behavioural reasons. Homes with fewer bedrooms, improved insulation levels and busy lives appear to side with electric heat. Larger homes and households are more positive towards gas (or district heating) systems.

The perceptions of occupants about future electrification of heat, energy sources and possible impacts show occupants had positive perceptions regarding the electrification of heat, but this is tinged with reservations based on the previous experience of cost, some inconvenience and levels of possible pollution at the place of electricity generation. The survey shows that nearly 62% of respondents have in fact lived in homes heated solely by electricity.

Overall, occupants are positive towards accepting the current pollution levels for longer until carbon capture and storage is implemented, paying higher prices for peak period energy demand, and the generation of renewable electricity locally. More concern is expressed toward additional construction works in apartments to facilitate future heat systems. Householders suggest that the trend of electrification of heat seen in cities is mainly due to electricity having a wider range of uses than other energy types and safety issues surrounding the use of gas in apartment blocks.

The local generation of electricity and heat was considered overall positive except for those technologies hinting at localised pollution such as biomass and heat from waste. The use of different energy types at different times was also seen as reasonable.

Occupants expressed their interest in deciding their own energy contracts and tariffs, the level of independence and control over their energy supplies and who should be their providers. Nevertheless, the surveyed householders appear to be aware of the implications and impacts of shifting pollution.

Householders have drawn on their experience and perceptions of organisations and their track records in determining trust to run community systems, denouncing utilities and private service companies in favour of local authorities and community groups.

Occupants consider the costs of running their energy systems as an issue however the importance of energy as a household cost is considered below that for transport and telephone, broadband and water combined – however, the average age of respondents was comparative low – the majority of respondents to the online survey were under 34 years of age 53% and therefore possibly represented a narrowing of opinions in this respect. Those using electricity for heat are generally paying more per annum compared to gas for heat households. Nearly 12% overall in the study are considered to be in fuel poverty, however as suggested by Fuller (2012), ‘fuel poverty’ remains a rather circumscribed concept, where wider issues of vulnerability and inequality may pass unnoticed as a result.

Overall, occupants concerns and interests about the electrification of heat were five-fold:

1) *The cost of electricity compared to other fuel types* – cost of the fuel to the householder is the main determining factor. Whether the system is electric, gas or heat pipe is not that relevant as long as it is economical.

2) *Comfort with existing heat-providing systems* – occupants have experienced different heat-providing systems, here more than 60% have encountered electric heat. There is a reluctance however to change particularly where gas fuelled systems and radiators are already installed or major construction inconvenience may occur.

3) *Control over their system* – householders wish to maintain control over their heat system and how and to who they pay for its provision. There is a reluctance to be involved with intermediary companies such as ESCo's preferring to deal directly with main fuel suppliers.

4) *Environmental considerations* – occupants are positive toward improvements in the environment through reduction in pollution etc. although the depth of their interest and commitment could not be measured through this study.

5) *Reasons for electrification of heat* – from the occupants' perspectives this is seen as a safety issue in apartment blocks and one where the electric system is already available and so makes sense to use it for heat as well.

6.4 Survey of stakeholders in organisations

Semi-structured interviews were conducted with a range of organisations to establish the reasons for the present trend and for and a possible future of electrification of heat in UK urban areas. The organisation stakeholders interviewed include: electricity and gas supply organisations, housing associations, developers, electrical appliance manufacturers and government offices. Selection was made based on organisations with roles, responsibilities and perspectives on heat electrification. In total, 23 people were interviewed in 21 organisations. Interviewees held positions ranging from Chief Executive Officers, Organisation Chairpersons, Programme and Project Managers, Operation, Network and Planning Managers, Consultants, Business Owners, Sales Representatives and Resident Committee Founders. Organisations interviews were conducted from the perspective of individuals representing organisations and were based on their clear opinions and feelings.

The methodology for the interviews has been described previously in Chapter 3. Emphasis has been placed on the context in which the participant's remarks are embedded. The guide questions used during the interviews can be found in 19 Appendix 9.

After each interview, the narrative was typed up ready for coding, conceptualising and categorising according to the *grounded theory* methodology and discourse analysis (Allen, 2003) – described in Chapter 3; this process was assisted through the use of QSR NVivo8 software (International, 2011). First, key points (nodes/*themes*) within the structure of the interview (or case study) were detailed. From each of the key points noted, *Codes* or *themes* emerged from the text, with the possibility of there being more than one *Code* from each text studied. Codes that relate to a common theme were then grouped together and these formed *Concepts.* Concepts were grouped and regrouped to find higher order commonalities called *Categories*. The concepts and linked categories then led to the development of *Hypothesis* that is grounded in the original data.

The overall aim of this process was to find out from the abundance of qualitative data two things:

1) Identify significant and common key points and categories from the range of interviews providing a framework of indicators and data for subsequent social and technical assessment of residential heat providing supply in cities; and
2) Draw conclusions concerning the electrification of heat through the grounded theory method.

The constant comparison technique has been used during grounded theory development especially the flip flop technique (Corbin, 1990); this has facilitated the analysis of contradictions.

6.4.1 Stakeholder interviews

Key points and codes

From the interview narratives key points were identified and codes derived – this was used as a way of linking the data to ideas and then from ideas back to the supporting data - an example of the process is shown in Table 42 with the complete coding analysis outlined in 20 Appendix 10. The process followed was to identify the key points and then concentrate the analysis on these through noticing and merging key points, codes and subsequently concepts and categories. As an example of the process; a common key point made during interviews was the cost comparison of electricity to gas – this would infer a code of 'cost' and this is highlighted, whereas occupants' switching of fuels, again a common theme, is predominately made only where it is 'cost effective' thus forming the next code. The key points and the subsequent codes were then grouped under common themes (at this stage following the interview guide themes) – this is further illustrated in Figure 139 and shows a typical model from the interview analysis process.

The outcome of the process is the emergence of codes that contribute to the concepts - seen here to the right of the figure. The codes grouped under the guide themes are compared with other codes – this is described next in the next section.

Table 42 Example from organisation interviews of the emergence of codes from key points and common themes.

[Guide theme is used for broad grouping purposes and relates to the original interview questions].

Key points (points regarded as important to the investigation)	**Codes**	**Guide theme**
Indicators for electrification of heat: Electricity more expensive than gas Occupants only switch if cost effective Electrification of heat (gas to electricity) needs sizable incentives Customers could be persuaded to switch through technology changes but would require national scale conversion Current extent of heat electrification through installation of heat pumps unclear Modern form of electric heating already installed through social assistance programmes House developers install the cheapest heating systems Passive house continues to need electricity for heat recovery and heat pumps Mains gas is first choice fuel for occupants because it is cheapest.	Cost Cost effectiveness Switch through technology changes Technology progress unclear Support within social housing Electricity always needed Gas first choice Incentives important Inner city trend Electric volume through heat services	Planning main drivers and demand

The renewable heat incentive is established to start delivering on heat by electricity Trend seen in inner city properties where more electricity is being used – both storage heaters and panel type heaters and some ASHP - most properties are flats and apartments When considering electricity volume - the only way is by looking at the heating services and take volume away from the likes of gas, oil etc. Heat service penetration is only 5-6% but if that is 20-25% that could be very substantial for the industry Disagree that there is a change from gas to electricity but a change from individual gas to centralised forms of gas sourced heat supply to apartments Upstream generation is not the only solution to an electric future – reforms, infrastructure development strategy, and smart meter rollout are important to support an energy shift.	Electric heat service penetration small More individual gas to centralised gas Upstream and downstream electric focus needed.	

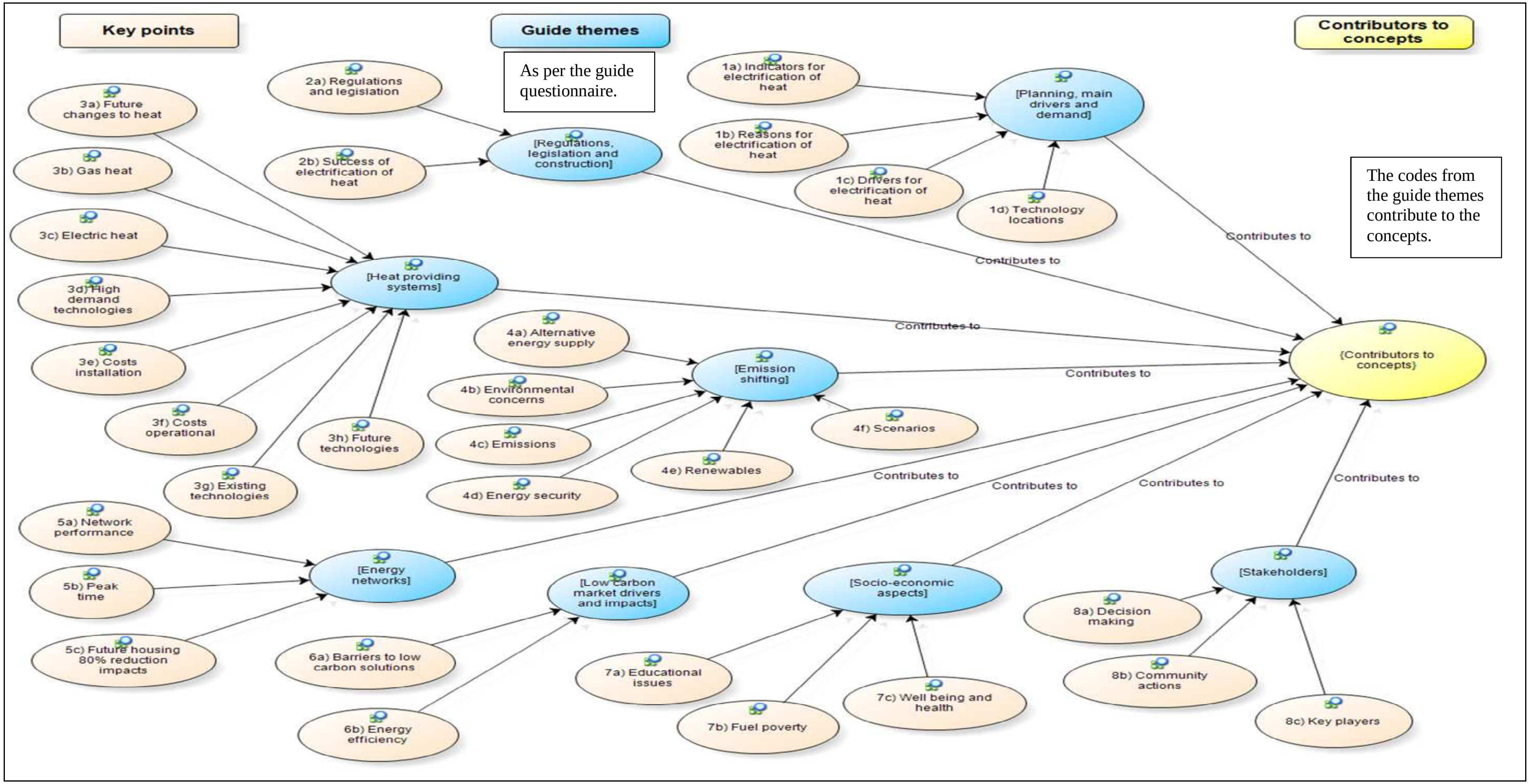


Figure 139 Emergent key points and codes within the defined themes that contribute to the development of concepts using grounded theory.

Concepts and categories

Commonality between codes was highlighted by comparing the codes with similar codes that had been derived from the key points. Common characteristics between codes from the various interviews provided a series of concepts – an example of the process is shown in Table 43. During the comparison of each concept with all other concepts, further broader categories were found using the constant comparison method (QDATRAINING, 2013) and the use of NVivo to facilitate the process. NVivo provided a platform where the narratives, key points and developing concepts could be easily managed.

In the example given in Table 43, categories relate to peak demand, clustering impacts and network management, storage and control concerns. The categories were highlighted within six headings: technology, carbon, interaction, demand, heat, regulations and cost. By linking the categories and investigating the connections between concepts, theory or hypothesis emerges – this process and model is further illustrated in Figure 140.

Table 43 Example from organisation interviews of the emergence of concepts and categories from codes.

[Guide theme is used for broad grouping purposes and relates to the original interview questions].

Codes	**Concepts**	**Categories**
		Demand implications
Peak demand major concern Clustering constraints More dynamic networks Storage at low demand times Behaviour change through peak time pricing and credits Real time information for load extent	Peak demand is major concern Peak pricing, credits and mistiming Changing of demand profile through demand flexibility, pricing and management Fuels working together	Peak demand issues
Optimising demand response to limit peak Network savings through smart metering	Clustering effects and constraints Dynamic network using real-time information and pro-active energy use management	Clustering impacts
Reducing new network assets through managing loads Mistiming energy Over capacity or consumer demand flexibility Demand profile changes Clustering effects of mono-systems Proactive energy use management. Reduction in infrastructure requirements Base load electric heating and gas top up Start-up currents Network operator obligations	Network savings through smart use Heat storage at low demand times Obligations of network operators	Network management, storage and control concerns

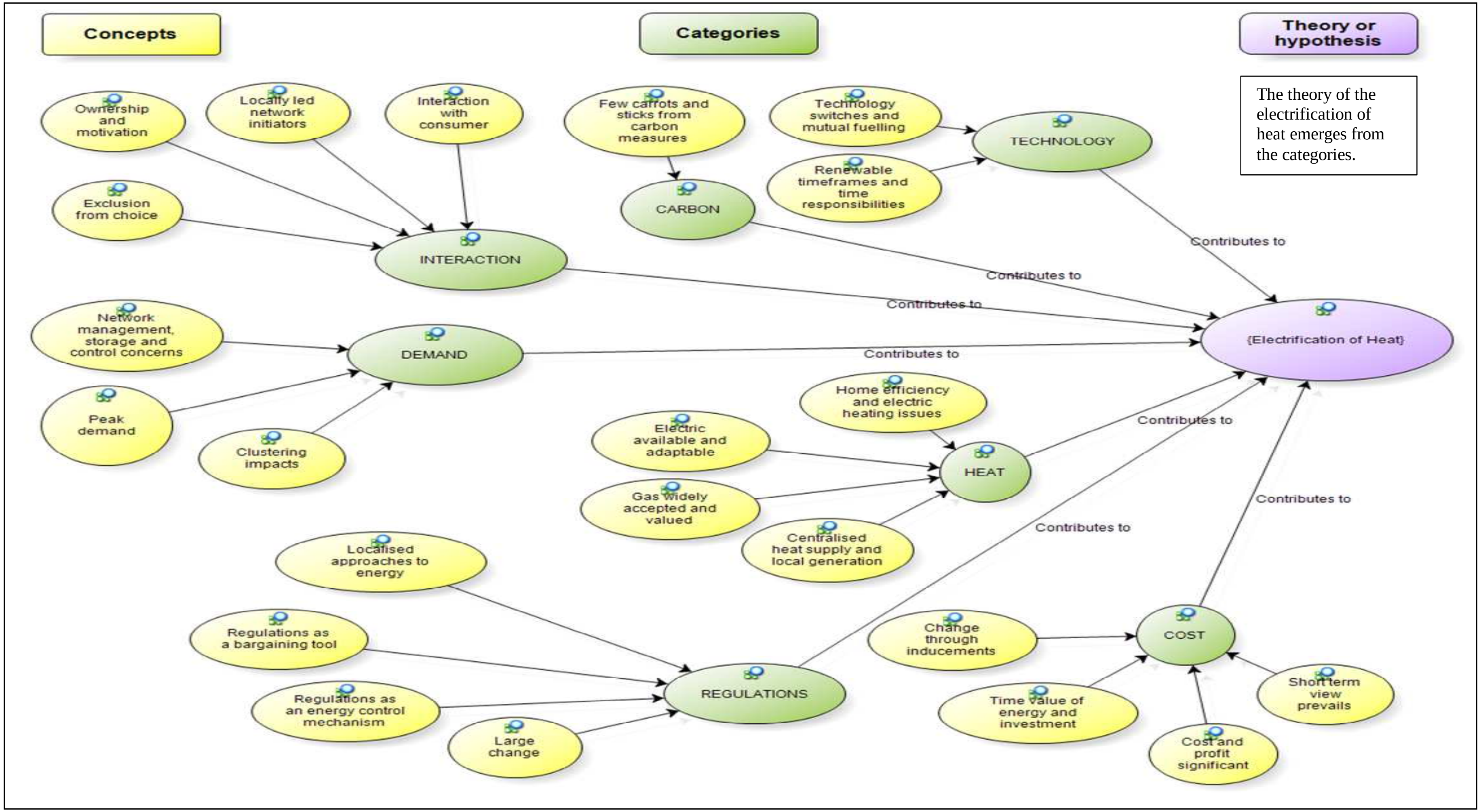


Figure 140 Emergent concepts and categories that contribute to the identification of indicators and the emerging of theory of electrification of heat.

6.4.2 Identification of indicators results

The categories that emerge from the grounded theory were detailed as:

- Technology
- Carbon
- Interaction
- Demand
- Heat
- Regulations; and
- Cost.

The categories shown above were retitled to reflect the scope of the contributing concepts and the relationship with the key theme of electrification of heat. Two additional categories were also added to show the development of the security of supply and fuel resilience aspects, the revised categories and what they show as indicators are now detailed:

> *Support to technologies* – this is a measure of the technical and program support required to technologies and their systems to enable each to function effectively and efficiency. It considers timeframes, energy efficiency measures, centralisation approaches and control requirements.
>
> *Carbon measures and concerns* – wider carbon concerns for each system are expressed within the environmental criteria; here stakeholders provide a measure of their carbon perceptions relating to heat-providing systems and an expression of impacts that carbon measures have in urban areas.
>
> *Interaction and ownership* – is an important aspect relating to the extent and opportunity of community involvement in domestic heat provision. Consideration is given to customer interaction with providers, inclusion or exclusion from wider energy choices, and the hassle factor concerning system operation and management.
>
> *Demand implications* - with increasing or dramatically changing energy demands there are implications on the energy supply systems especially electricity and gas. This indicator provides an overview of the supply system impacts connected with each technology and impacts from demand and time pricing.

Diversity of heat - diversity of heat is seen as a positive characteristic and one that offers greater choice and flexibility to a system. This indicator reflects the comparison of systems based on local storage capabilities, provision requirements and future system adaptability.

Development implications – this is a measure of the stakeholders views on developmental aspects of urban energy including preferences, transformational implications, localised approaches and regulatory manoeuvring.

Social timing – this expresses the overview of householders opinions related to costing dynamics, system lock-in, incentives and time related implementation issues.

Fuel resilience – this indicator reflects dependency of a technology and system on imported or restricted fuels possibly reducing flexibility and subject to price volatility.

Low income – high cost measure – a low income and the increasing cost of fuel and heat system operation can lead to fuel poverty. This indicator is a basic measure of fuel poverty vulnerability as reflected from the heat system type and associated factors such as fuel cooperation opportunities, and wider choice exclusion.

Finally, each of the above indicators and the contributing concepts were rated on a scale of 1 to 6 (best to less good) for each of the studied heat providing systems – the summary spreadsheet of the determined values is shown in 19 Appendix 9.

6.4.3 Emerging theory of electrification of heat results

At this point, the categories shown in Figure 140 were defined through the linking and investigating of all concepts and prior to this - key points using NVivo and constant comparisons. The relevant group of questions used during the interviews supported this process through the provision of focus but not preconceived bias. However, grounded theory requires that, in order to develop theory, categories must emerge from the common themes and these categories then move into developing theory. This is performed through the embedding of the categories into the theory summary. Therefore, based on Figure 140 and the summation of data in 20 Appendix 10 the emergent grounded theory of electrification of heat can be summarized as follows:

> "Electrification of heat is a recent and developing trend using electricity at the district, community or household level to provide heat for household needs. Although natural gas is widely accepted and valued as a domestic heating option, improvements to home efficiency and the construction of smaller city homes have supported the use of electricity for heat requiring lower heat demand and less extensive systems. The trend has been promoted, especially by developers where clustering of mono-heating systems have occurred principally in city areas. The usefulness of electricity particularly for heating may be compromised where legislation and regulations are used as an energy control mechanism or bargaining tool. This is particularly evident through the use of fuel factors related to carbon intensity but not necessarily the timing of energy use. The variability and impacts from the few carrots and sticks approach taken by current carbon measures produces an unclear and unsatisfactory roadmap for heat from electricity. Renewables will assist in provisioning low carbon electricity; nevertheless, realistic timeframes for their implementation and time responsibilities are paramount to continue the synchronisation of city supply systems.
>
> Further scaling up of electrification of heat would entail a monumental change akin to gas conversion investment and reconstruction and require network supply development and implementation including management, control and energy storage. However peak demand and the clustering of the same energy technologies can make the further use of electricity difficult and expensive to support unless localised approaches and continuous interaction between suppliers and consumers are employed.
>
> A centralised locally initiated and owned heat supply system using duel fuelling or technology switching may offer an alternative to the electrification of heat. It is important however, that any approach prevents exclusion from choice but reinforces the sense and practice of system ownership or buy-in."

6.4.4 Relationship assessment results

Stakeholders from the interviewed organisations were asked to rate theirs and other stakeholder positions on a scale of (1 to 10) where 10 has the greatest impact using three criteria:

- *key players* – the decision making capacity or involvement of various stakeholders on the electrification of heat;
- *influence on decisions* – the influence of various stakeholders on the electrification of heat: and
- *impacts from decisions* – the medium to long term impacts on recipient from decisions especially relating to costs, changes of situation etc.

The results of the assessment based on the aggregation of data are shown in Figure 141. Key players identified in the study include: local authorities (8), utilities (8), regulatory organisations (8), and electricity generators (8). Those having the most influence on the electrification of heat, as seen by other stakeholders include: national and regional governments (9), regulation organisations (9) and government offices. Impacts from the decisions taken are experienced most by, occupants (10) and fuel cost burden sufferers (10).

The role of building developers in deciding on the type of energy system to be installed in a building is significant (8) but they take little impact from their decisions (score of 2). Where only social housing is concerned, local authorities and housing agencies are important in the final decision making processes (score of 7 and 6 respectively), however residents organisations take a high impact from decisions (8) but are neither seen as key players nor influencing decisions (scores of 4).

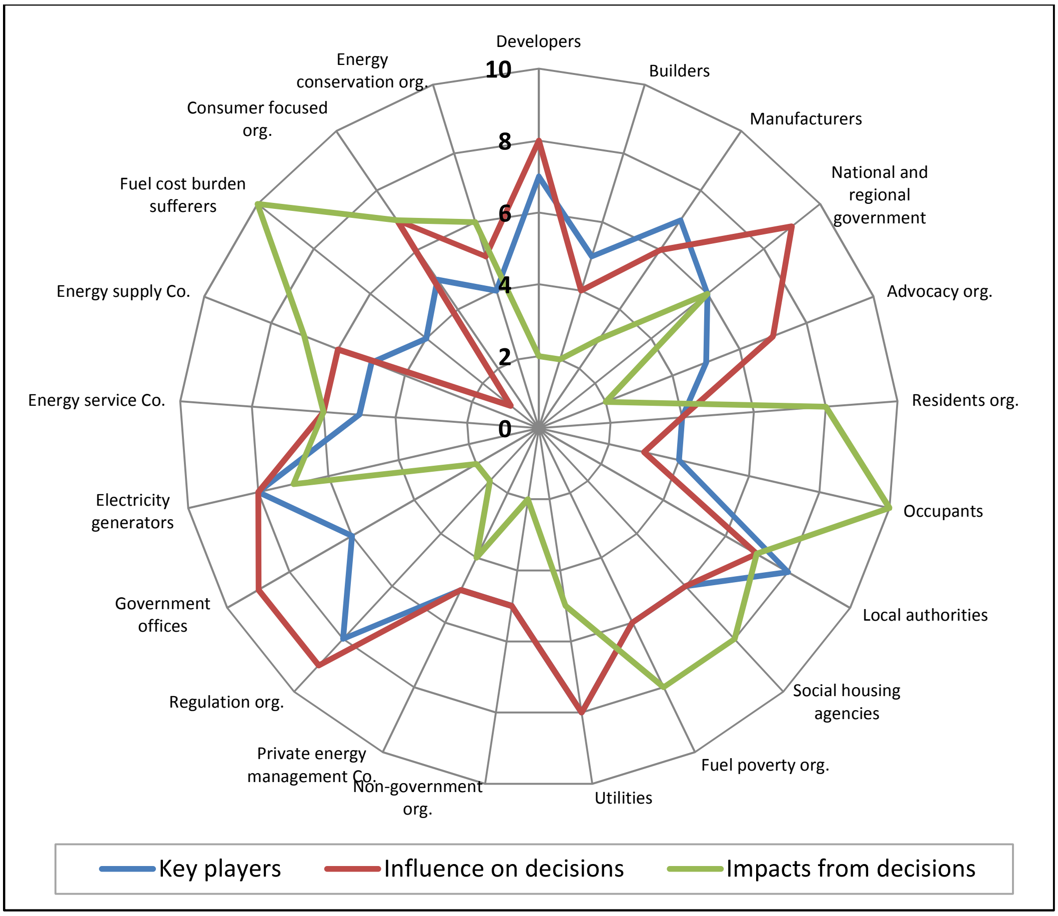


Figure 141 Key player and their influence on decisions related to the electrification of heat.

[Based on a scale of 1 to 10 where 10 is key player, most influence and receiving most impacts from decisions].

6.4.5 Discussion of the results

As summarised in section 6.5.3, it was found out that the eighteen identified categories and 64 of the concepts are embedded in the emergent grounded theory. Based on grounded theory (Strauss and Corbin, 1998), the resultant theory does not need separate justification or testing as it came from the original live data. Nonetheless, a brief discussion of the key features under each of the final *category* headings and subsequent indicators is presented below and related to the objectives of this work with respect to the electrification of heat.

Support to technologies: In terms of current electrification of heat, the predominant technology is heat pumps. Low-carbon technologies have both installation and future maintenance issues that discourage developers and housing organisations while poor maintenance information also deters occupants. Centralised common heat systems rather than individual systems are seen by building planners and some developers as a popular alternative combining adaptability with duel fuel approaches and generation.

Carbon measures and concerns: People and organisations are genuinely concerned about their carbon footprints and there is a growing awareness and knowledge of carbon impacts. Electricity generation shifts emissions from urban to remote areas; however, with small and medium-sized localised electricity plants being developed a dilemma exists. Where there is much less pollution through power generation than previously experienced in the urban environment, there is more concerns than previously from an enlightened public.

Interaction and ownership: Organisations recognise that energy utilities and private organisations are often perceived by consumers as faceless and exploitative and realise that improved interaction with customers can result in joint energy and cost savings, and diminish customer powerlessness and exclusion from energy choices. Locally led and supported energy initiatives between communities and other stakeholders such as local authorities and developers can provide a shared ownership approach supporting the improvement of motivation for energy efficiency, quality of life and overcoming the hassle factor of energy improvements.

Demand implications: Present electricity demand for heat is limited compared to natural gas. Although peak electricity demand is a concern for electricity generation and network providers, expected changes through demand flexibility by householders, network management by network providers, and pricing by energy suppliers may flatten the demand profile. The local storage of energy either as heat or electricity could be required to reduce infrastructure expenditure.

Diversity of heat: High insulation levels and well planned electric heating go hand in hand. Electricity is always needed and can be fed from any appropriate source although the trend to date has been built predominately on a short term private sector development initiative. Drawing on the emergence of concepts from the interviews, further electrification of heat is not only to be built on upstream large-scale generation but downstream efficient utilisation particularly focussing on heat pumps.

Development implications: Recent building regulations and compliance tools consider electric heating negatively other than heat pumps which share the same emission factor but exhibit better efficiency and will wait for the decarbonising of electricity before a fundamental change. Developers and large scale initiators may drive energy changes through regulation manoeuvring and scale by using combined energy schemes and large scale mono-technology programmes.

Social timing: Concerns about immediate or short term costs rather than carbon costs were often highlighted, with profit being a significant player in any initiative. The value of avoided energy through system enhancement is missing. For example, improved insulation would avoid the use of a quantity of energy – this avoided energy is not valued directly at scale. Incentives are important where spending on properties for energy saving is not a priority or technologies require promotion. The time cost of energy use at particular times of the day will become significant as management and control mechanisms that link the supply network to household digital appliances and heating control systems come online. The importance of incentives for energy efficient improvements and renewables was highlighted throughout concluding that these could encourage higher take-up.

Stakeholders: Reference was often made to low-income households, those suffering the burden of fuel cost and those in the fuel-poverty category – it is recognised that they often have little influence and are dependent on others. Furthermore, contradiction of roles is observed with great distrust in organisations that are trying to sell occupants energy and then trying to save occupants energy at the same time. Organisations refer to stakeholders as 'those involved in the supply chain of energy' whereas occupants see other stakeholders from the point of view of contact, i.e. the council, the gas or electricity company. Stakeholders or 'players' tend to operate in their own sphere; however, decentralising and network management are helping to develop new approaches and relationships between them.

6.4.6 Summary

A series of face-to-face and online surveys have been conducted with occupants of apartment blocks. These have provided insights into occupants thinking and feelings of their current and future energy systems and electrification of heat. Key stakeholders and decision makers have been identified and semi structured interviews have taken place with several organisations involved at different roles in energy provision to cities. Analysis of the results obtained in the interviews was conducted using grounded theory. A summary of the key findings now follows.

Online survey

- At the household level, occupants recognize that a switch from gas to the greater use of electricity for heating has occurred in places and that this has happened in newer or retrofit buildings constructed with a smaller number of bedrooms.
- Although effective in use, apartment occupants view electric systems as expensive to operate. There is an appreciation of gas space heating especially amongst those whom have experienced this type of system.
- All electric heat systems and homes are seen as low indoor polluters and safer overall but less positive toward paying more for peak demand electricity or maintaining current pollution levels from power generation for longer.
- Occupants using alternative heat providing systems such as the combined gas and electricity system view them positively in terms of their efficiency but are

wary of third party involvement particularly regarding pricing, lack of choice and transparency.

- Occupants are positive toward local generation but few have experienced this directly. From the survey, nearly 12% are in fuel poverty; nevertheless, fuel and the related heat are not the main priority for household expenditure.
- Overall occupants would like greater control and independence over their heat supply system.

Organisation survey

- Organisations' perspectives vary considerably depending on their working context; however, commonalities have emerged allowing a grounded theory to be developed.
- Electrification of heat is seen as a short term event or trend in cities where developers and others have taken advantage of a transient regulatory structure and flexible implementation. However a new form of heat electrification is on the horizon particularly through the use of heat pumps.
- Any substantial move from gas to electricity for heat would require a monumental change involving considerable additional investment, and new approaches of working and interacting with networks and customers.

The environmental, economic and social sustainability have been discussed and results determined within Chapter 4, Chapter 5 and Chapter 6. The following chapter on Multi-criteria decision analysis describes how MCDA can be used in sustainability decision making.

7. Multi-criteria decision analysis (MCDA)

Following on from the life cycle analysis, life cycle costing and social analysis, this chapter illustrates how the results of sustainability assessment can be used to inform decision making. To help deal with the large amount of data and information, multi-criteria decision analysis (MCDA) is used taking into account potential preferences for different sustainability criteria. The aim is not to find an ideal or optimum solution but to illustrate how the sustainability ranking of different heat systems may change based on different preferences and how that may help to inform decision makers.

7.1 Introduction

7.1.1 Aims and objectives of MCDA

The main aims of this analysis are:

- to identify the most sustainable heat-providing systems based on different preferences for the environmental, techno-economic and social aspects studied in this research; and
- to determine the dominant parameter(s) and the significance of others in defining the overall sustainability of heat-providing systems.

7.1.2 Assumptions and limitations

The following assumptions and limitations are considered:

- Only residential heat energy is considered – space, water and cooking heat.
- Evaluation is primarily based on the 2010 data in terms of electricity generation, natural gas mixes and impacts.
- Life cycle stages contributing little to the impacts across the systems are removed from the analysis – i.e. decommissioning, disposal and transport.
- Preferences for different sustainability aspects are hypothetical as stakeholder consultation was outside the scope of this study.

7.2 Identification and selection of decision criteria

The decision criteria have been selected using the sustainability indicators obtained through environmental, techno-economic and social analysis and discussed in Chapters 4, 5 and 6, respectively. These are summarised in
Table 44 and detailed further below. Results from each of the sustainability assessments have been normalised. The values used in this study are shown in 21 Appendix 11.

7.2.1 Environmental criteria

The following life cycle environmental indicators are considered, as obtained in LCA:

- Acidification potential (AP);
- Eutrophication potential (EP);
- Fresh water aquatic eco-toxicity potential (FAETP);
- Global warming potential (GWP);
- Marine aquatic eco-toxicity potential (MAETP);
- Ozone depletion potential (ODP);
- Photochemical ozone creation potential (smog potential) (POCP); and
- Terrestrial eco-toxicity potential (TETP).

In addition, indoor pollutants studied in the IAQ research (Chapter 4) are also considered, i.e. the emissions of CO, CO_2, NO_2, and SO_2.

7.2.2 Techno-economic criteria

Economic indicators provided by the study LCC and described in chapter 5 include:

- Capital cost – investment cost relating to manufacture, purchase and installation of heat providing technologies and associated supply system over the 40 year period.
- Operation & maintenance (O&M) – all costs involved in the operation and maintenance of the technology and system but excluding energy costs over 40 years.

- Fuel cost – refers to the cost paid by householders for the supply of the required energy through the associated supply system during the 40 years.
- Annualised cost per kWh – cost of capital, O&M and fuel per kWh of energy supplied over 40 years.

Technical indicators are drawn from the online and face-to-face stakeholder surveys and provide a summary technical appraisal and qualitative assessment based on stakeholder reflections on system performance and capabilities. Data are drawn from the stakeholders' surveys and are qualitative in nature. The following technical criteria are considered:

- System effectiveness and efficiency;
- Safety, regulations and uses;
- Heat technologies and energy sources;
- Heat control and management;
- Diversity of heat;
- Demand implications;
- Support to technologies;
- Carbon measures and concerns; and
- Fuel resilience.

7.2.3 Social criteria

Social indicators are provided from the stakeholder surveys and are qualitative:

- Social timing;
- Development implications;
- Interaction and ownership;
- System perceptions and experience;
- Acceptability of upstream factor; and
- Low income – high cost measure.

The final three social indicators, obtained in the LCA study, are: depletion of abiotic elements (ADP_{el}) and fossil fuels (ADP_{fossil}) and human toxicity potential (HTP). They are considered to be social issues as the first two are related to the availability of resources for future generations and the latter to human health issues. These indicators were described in detail in Chapter 4.

Table 44 Criteria for MCDA – environmental, techno-economic and social criteria.

Aspects	Criteria	Units	Score type
Environmental	AP	(tonnes SO_2 eq.)	Quantitative
	EP	(tonnes PO4 eq.)	Quantitative
	FAETP	(tonnes DCB eq.)	Quantitative
	GWP	(tonnes CO_2 eq.)	Quantitative
	MAETP	(tonnes DCB eq.)	Quantitative
	ODP	(tonnes R11 eq.)	Quantitative
	POCP	(tonnes C_2H_4 eq.)	Quantitative
	TETP	(tonnes DCB eq.)	Quantitative
	Indoor CO	(mg /m^3)	Quantitative
	Indoor CO_2	(mg /m^3)	Quantitative
	Indoor NO_2	(µg /m^3)	Quantitative
	Indoor SO_2	(µg /m^3)	Quantitative
Techno-economic	Capital costs of system	(£ billion)	Quantitative
	O&M costs of system	(£ billion)	Quantitative
	Fuel costs of system	(£ billion)	Quantitative
	System cost per kWh	(£ /kwh)	Quantitative
	System effectiveness and efficiency	Dimensionless	Qualitative
	Safety, regulations and uses	Dimensionless	Qualitative
	Heat technologies and energy sources	Dimensionless	Qualitative
	Heat control and management	Dimensionless	Qualitative
	Diversity of heat	Dimensionless	Qualitative
	Demand implications	Dimensionless	Qualitative
	Support to technologies	Dimensionless	Qualitative
	Carbon measures and concerns	Dimensionless	Qualitative
	Fuel resilience	Dimensionless	Qualitative
Social	Social timing	Dimensionless	Qualitative
	Development implications	Dimensionless	Qualitative
	Interaction and ownership	Dimensionless	Qualitative
	System perceptions and experience	Dimensionless	Qualitative
	Acceptability of upstream factors	Dimensionless	Qualitative
	Low income – high cost measure	Dimensionless	Qualitative
	Depletion of elements (ADP_{el})	(tonnes Sb eq.)	Quantitative
	Depletion of fossil fuels (ADP_{fossil})	(GJ)	Quantitative
	Human toxicity potential (HTP)	(tonnes DCB eq.)	Quantitative

7.3 Results from sustainability assessment through multi-criteria decision analysis

The MCDA has been carried out using the MAUT/MAVT approach modelled in the software *OnBalance* (Quartzstar, 2010). Equal weighting has been assumed for all the criteria and the influence of changing the weights explored through a sensitivity analysis.

7.3.1 Ranking of the systems when all sustainability aspects are equally important

The total ranking for each system based on equal weights is shown in Figure 142. The breakdown of results for the environmental and techno-economic criteria is given in Figure 143 while the results for the remaining techno-economic and social criteria can be found in Figure 144.

As indicated in Figure 142, the district heating system is the preferred option (overall score of 20.7) when all the sustainability criteria are considered. However, the solar thermal gas 22.0 and the CHP 22.4 systems both come close to the district heating system despite differing values for a number of criteria. The electric panel system is the worst option (overall score of 70.5) with particularly high scores in the environmental 23.3 and social 24.8 categories and is closely followed by the electric storage 24.7 and 22.6 respectively and communal ASHP 18.5 and 18.3 respectively – all are electric heat systems. It can also be noticed that there is a notable difference of values between the best and worst performers and a spread of system results between the two – the 'mid-point' is dominated by the combined and individual gas boiler systems. The gas based systems perform well within the environmental criteria 11.2 but generally perform less well economically 22.2 except for energy costs and subsequently the overall cost per kWh. With equal weight assumed for all the criteria, the electric heat systems (panel, storage and ASHP) are therefore the worst performers.

The results for each system using the techno-economic and social indicators from Chapter 5 and Chapter 6 respectively are now discussed.

- *System effectiveness and efficiency* – this is an indicator of the heat system efficiency and effectiveness in providing heat to the household. The CHP and district heating systems are ranked the first and second with the individual gas boiler a close third. These systems represent even heat predominately through wet heating systems and at costs that are considered acceptable. The all-electric systems perform the worst.
- *Safety, regulations and uses* – reflects on the range of reasons concerning heat electrification and applies these to each of the heat providing systems. The

individual gas boiler and combined solar and thermal and gas systems are the worst performers reflecting the safety issues and design requirements around gas in buildings. The best performers are the all-electric systems with easier installation requirements, better safety and lower space heat supply and demand as building insulation is improved.

- *Heat technologies and energy sources* – shows how each of the heat providing systems is assessed against the opportunity of renewable technology and system link in. The combined solar thermal and gas ranks first through its use of renewable energy whereas other systems predominantly only convert either electricity or gas to heat. Of the all-electric systems, the ASHP performs the best through its higher efficiency conversion of electricity to heat.
- *Heat control and management* – and represents the extent of heat system impacts related to control and management of heat. The combined heat and power system is ranked last and the ASHP second last. Both systems involve a lessoning of household control and independence over their supply with both systems provided by intermediaries.
- *Diversity of heat* – compares systems based on local storage capabilities and future system adaptability. The combined gas and electric system performs best with its range of heat from gas and electricity – the solar thermal and district heating systems are a close second. The indicator recognises the availability of storage in each system – cylinders or central thermal stores and the systems adaptability should fuel change in the future. The combined system could make use of biomass for example or locally generated electricity from PV or wind. The gas boiler is ranked last as this is solely dependent on natural gas.
- *Demand implications* – provides an overview of supply system impacts connected to each technology. The combined solar thermal and gas system is ranked first through its use of solar energy and heat storage - the district heating and CHP are equal second. Each system can help reduce peak energy demand on supply networks. The worst performers are the ASHP and electric panel system.
- *Support to technologies* – a measure of the technical and programme support required to technologies and their systems to enable them to function effectively and efficiently. Overall the CHP system provides the most responsive option through its ability to promote energy switching, its inclusive storage and dual

fuel availability. The poorer performers are the single supply systems such as the electric panel and individual gas boiler systems.

- *Carbon measures and concerns* – provides a measure of stakeholders perceptions relating to heat providing systems and impacts of carbon measures. The solar thermal and gas system contributes to carbon reduction through its use of renewable energy – this ranks the system first. The electric based systems particularly the panel and storage systems are ranked last due to their use of high carbon electricity.
- *Fuel resilience* – reflects dependency of a technology and system on imported or restricted fuels. The CHP ranks first through its generation of electricity and heat but also its adaptability to other supply fuels in the future. The individual gas boiler is ranked last through its sole dependency on natural gas.
- *Social timing* – expresses the overview of householders opinions related to costing dynamics, system lock-in and time related implementation issues. From the analysis, the solar thermal and gas system is ranked first and the electric panel last. The electric panel exhibits concerns relating to its association with fuel poverty and poor tariffs, the build and leave focus, lack of pricing against time usage and better deals through cooperation. The solar thermal system considers future avoided energy, and provides a benefit to those in fuel poverty.
- *Development implications* – a measure of stakeholders views on developmental aspects of urban energy. The district heating system is ranked first and the electric storage last. The former permits new routes to heat markets and the inclusion of incentives for development. Storage heating is threatened through regulations and policy to reduce or stop the use of less efficient electricity for heat.
- *Interaction and ownership* – relates to the extent and opportunity of community involvement in domestic heat provision. The solar thermal is first and the district heating, CHP and combined gas and electricity rank equal second. The electric panel, storage and gas boiler are last. The first four systems provide opportunities for communities, associations and householders to be involved in their energy supply systems whereas those placed last are directly supplied from utilities and interaction limited to only supplier selection.

- *System perceptions and experience* – This comparative indicator expresses the overview of opinions concerning system performance and intrinsic value. The centralised systems of district heating and CHP are ranked the best and ASHP, panel and storage the worst. Performance is considered less positive for the electric systems with economic constraints and less security of supply.
- *Acceptability of upstream factors* – represents occupants' views on upstream impacts from future electrification of heat. The solar thermal and gas and CHP are positively ranked and the ASHP ranked last. The former systems are able to generate additional heat or power that can be used by households and are not constrained by possible pricing differences from principle fuels.
- *Low income – high cost measure* – basic indication of fuel poverty vulnerability. The systems that are able to respond to fuel poverty dynamically are the district heating and CHP systems whereas those less able are the electric panel and to a lesser extent the electric storage system.

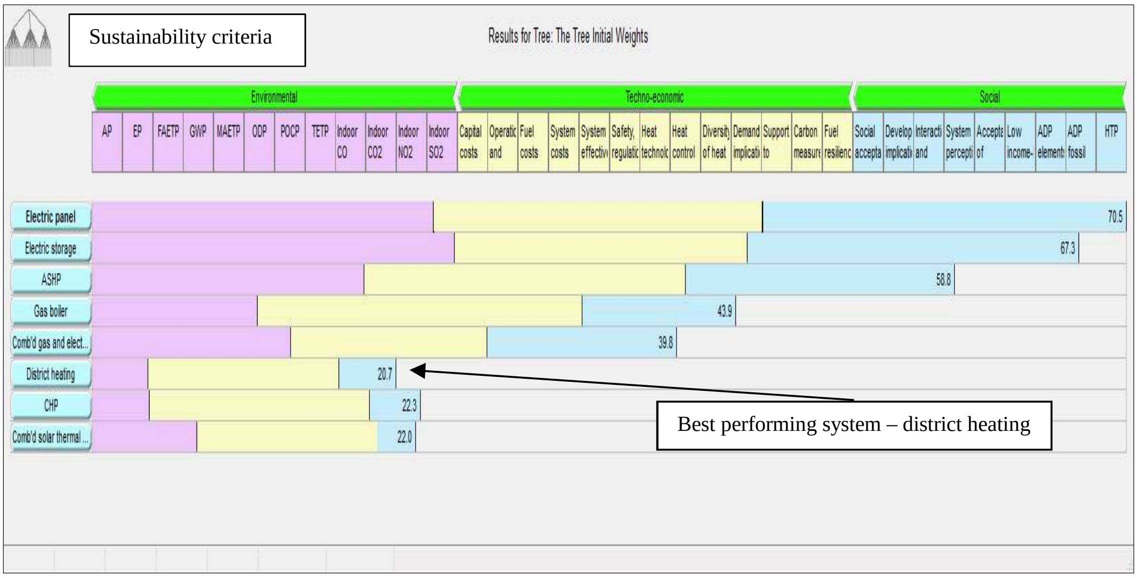


Figure 142 Ranking of each heat providing system against applied weighting.

[Total scores are shown for each system. Mauve, yellow and blue bars represent impacts for each sustainability category – environmental, techno-economic and social respectively].

Figure 143 Comparison of environmental and techno-economic criteria and overall MCDA result.

[Equal weighting, lower values are better].

Figure 144 Comparison of remaining techno-economic and social criteria and overall MCDA result.

[Equal weighting, lower values are better].

7.3.2 Ranking of the systems when environmental impacts are most important

When the environmental weighting in the MCDA model is doubled compared to the techno-economic and social weighting, the ranking of the systems remains essentially the same as described previously in 7.3.1. The best performing system continues to be the district heating 18.1 and the worst performing the electric panel 69.3 – see Figure 145. A change of rank occurred between the CHP and the solar thermal and gas system - the former now ranks second. The two gas based systems – the combined gas and electric system and the gas boiler retain their rankings at 4th and 5th with values of 39.4 and 40.7 respectively. The position change is from the CHP system benefit of avoided grid electricity as a proportion of this is generated from the CHP unit. The gas boiler is poorly positioned due to the indoor air quality criteria and emissions from the gas cooking.

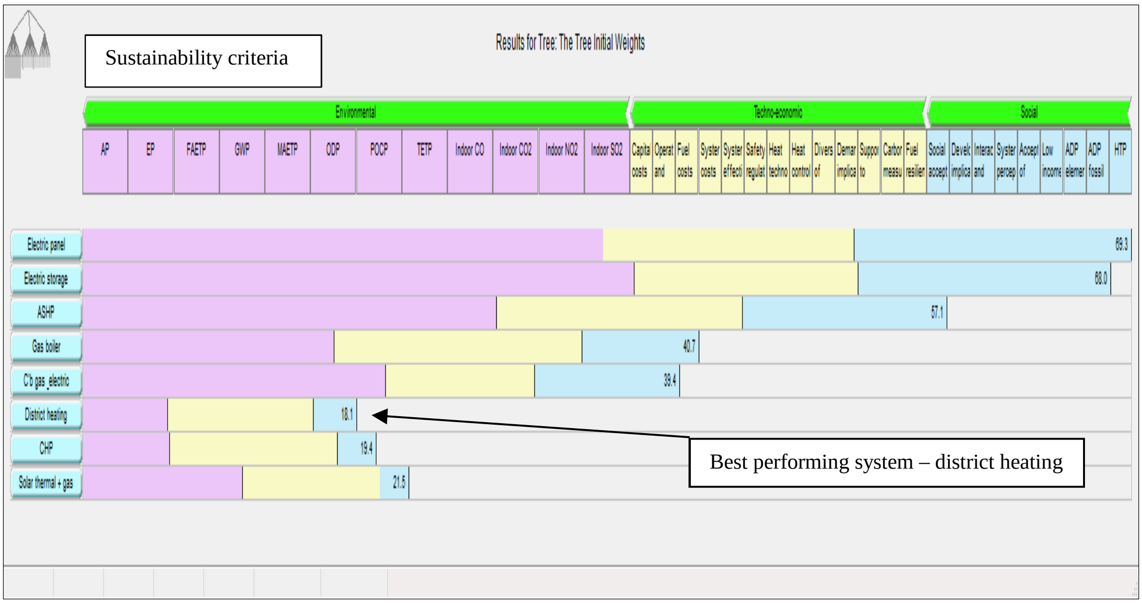


Figure 145 Ranking of each heat providing system against applied weighting where environmental impacts are most important.

[Total scores are shown for each system. Mauve, yellow and blue bars represent impacts for each sustainability category – environmental, techno-economic and social respectively].

7.3.3 Ranking of the systems when techno-economic impacts are most important

Increasing the weight by 100% of the techno-economic criteria as opposed to the environmental and social categories again retains the electric panel 67.3 and storage heating 63.2 systems as the poorer performers – see Figure 146. The best performer is the district heating system 24.4 despite its high capital and maintenance costs however, the solar thermal and gas system is very close at 24.9. In this particular model, the gap between the combined gas and electric system and gas boiler system has widened giving rankings of 4th and 5th - 38.5 and 47.8 respectively – the combined system has better safety, demand implications and diversity of heat factors than the gas boiler. The ASHP system is a disappointing 6th at 58.4.

Figure 146 Ranking of each heat providing system against applied weighting where techno-economic impacts are most important.

[Total scores are shown for each system. Mauve, yellow and blue bars represent impacts for each sustainability category – environmental, techno-economic and social respectively].

7.3.4 Ranking of the systems when social impacts are most important

Finally, when the social weighting is doubled and the environmental and techno-economic weighting remains the same as in section 7.3.1, the overall ranking again stays the same. The best performing is the district heating 19.4 and worst performing the electric panel system 75.4. The district heating, solar thermal and gas, and CHP systems are very close in value at 19.4, 19.5 and 20.4 respectively. In addition, the mid-point systems; the combined gas and electric and individual gas boiler systems are also close at 41.7 and 43.0. The three all-electric systems - the ASHP, storage and panel systems exhibit large differences at 61.0, 71.1 and 75.4 respectively and are weakened by poor system perceptions and experience and ADP element, ADP fossil and HTP impacts.

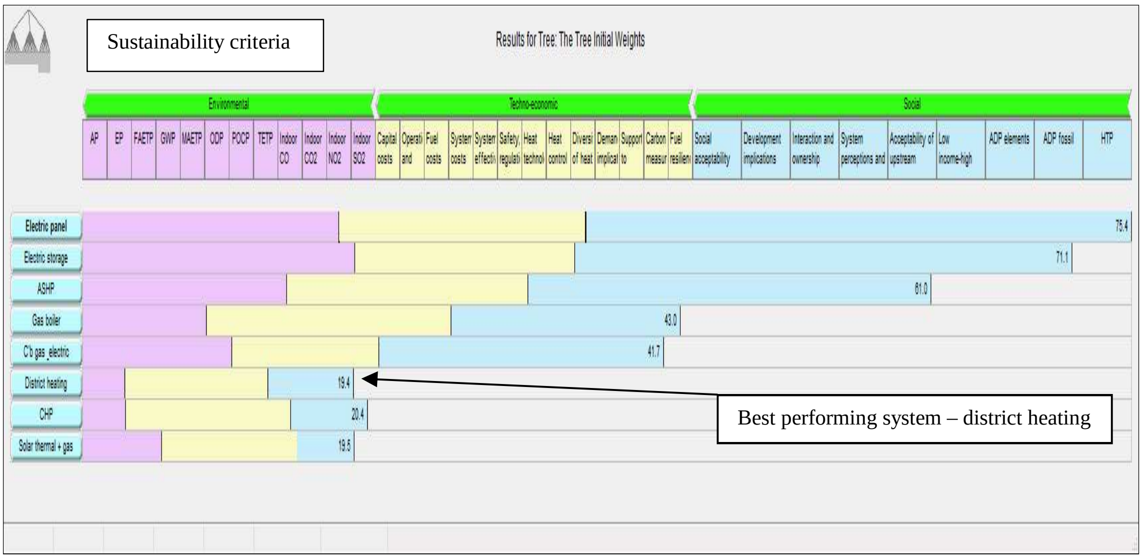


Figure 147 Ranking of system impacts according to MCDA where social impacts are most important.
[Equal weighting, lower values are better].

7.3.5 Ranking of systems with decarbonisation of electricity

As outlined in Chapter 4, most environmental impacts for the electric heat systems are due to the carbon-intensive electricity mix in the UK. Sensitivity analysis conducted in Chapter 4 on the environmental impacts of a change in the carbon emissions of the electricity mix concluded that a move toward a low-carbon mix as expected by 2050 could substantially reduce the overall environmental impacts of electricity systems. The impacts of such a change were studied for each of the heat systems through the MCDA modelling and include the techno-economic and social criteria.

The MCDA results were compared with those using a low carbon electricity mix as envisaged in 2050 while natural gas impacts remain similar to those of today. Overall, results for 2050 mix remain similar to the 2010 electricity mix for heat providing systems. The best performing system remains the district heating 30.8, and the worst, the electric panel 60.5 using equal weighting for environmental, techno-economic and social criteria – see Figure 148.

The move toward a low carbon mix however brings the heat systems closer together in terms of their overall MCDA results and produces two distinctive groups – those mainly using electric and individual gas boiler systems (poorer performers) and those predominantly gas fuelled community based systems (better performers). When the environmental impacts are compared to the techno-economic and social impacts, the preferable systems are the district heating and CHP systems respectively. The solar thermal and gas system is the most preferable system when the techno-economic impacts are compared with the social impacts for the same low-carbon energy mix. For each of the bi-comparisons – the electric panel and storage systems are again the least preferable options.

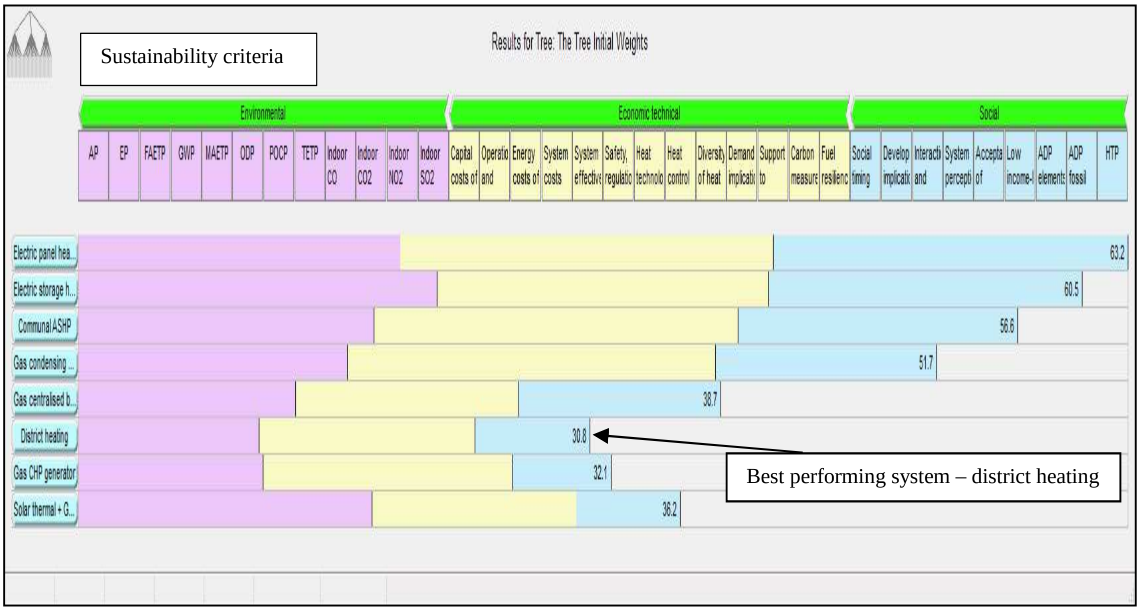


Figure 148 Overall MCDA for heat providing systems using low carbon electricity mix.

[Only a small number of criteria are shown for clarity along with the overall ranking].

7.4 Discussion of results

The ranking of the heat systems with equal weighting, and greater importance given to the environmental, techno-economic or social impacts shows a good consistency of ranks for each type of heat system. The best performer is consistently the district heating system, and the worst performer is the electric panel. The district heating performs best when importance is given to the environmental impacts, however across the weightings there is little change ranging from 18.1 to 24.4. The electric panel system performs best with weighting on the environmental 69.3 and worst on the social 75.4.

The solar thermal and gas system, and the CHP system also perform close to that of the district heating system for each weighting. The solar thermal is stronger for the techno-economic and social while the CHP is the better performer with the environmental weighting. The electric based systems (ASHP, storage and panel) perform poorly overall - ranked 6th, 7th and 8th respectively for all impacts. There is an average difference of 44% between the best performers (community based systems) and the worst (electric based systems). The gas boiler and combined gas and electric (gas based systems) are relatively equal mid-point performers for most impact ranking although there is a sizable difference 47.8 and 38.5 respectively for the techno-economic impacts.

A robustness diagram compares the best performing system with the poorest performing and enables the contrasting of differences between systems by looking at the specific mapped values and weights of each criterion used in the MCDA. The electric panel and district heating system (best and poorest performer respectively) are shown in the robustness diagrams - 22 Appendix 12 and Figure 150. The district heating system is taken as the baseline system as this was the overall best performer. All other heat systems are compared to the baseline showing the difference for each criteria starting with the largest difference, in this case – system effectiveness and efficiency, Figure 149. The robustness diagram continues with decreasing criteria differences between the electric panels and the baseline district heating – see Figure 150. The gas boiler and combined solar and gas system are also shown in the robustness diagrams.

From left to right across Figure 149 and Figure 150, the electric panel has higher values than district heating for 30 of the criteria leaving only four in favour of the electric panel - heat control and management, safety regulations, capital cost of system and O&M costs. The criteria in favour of the electric panel are those that generally deter developers from initiating and constructing larger communal schemes at present – see chapter 6.

Figure 149 Robustness comparison of electric panel and district heating systems for all criteria (part one).

[The baseline system is district heating and compared to the electric panel system. The solar thermal + gas, and ASHP system are included for comparison].

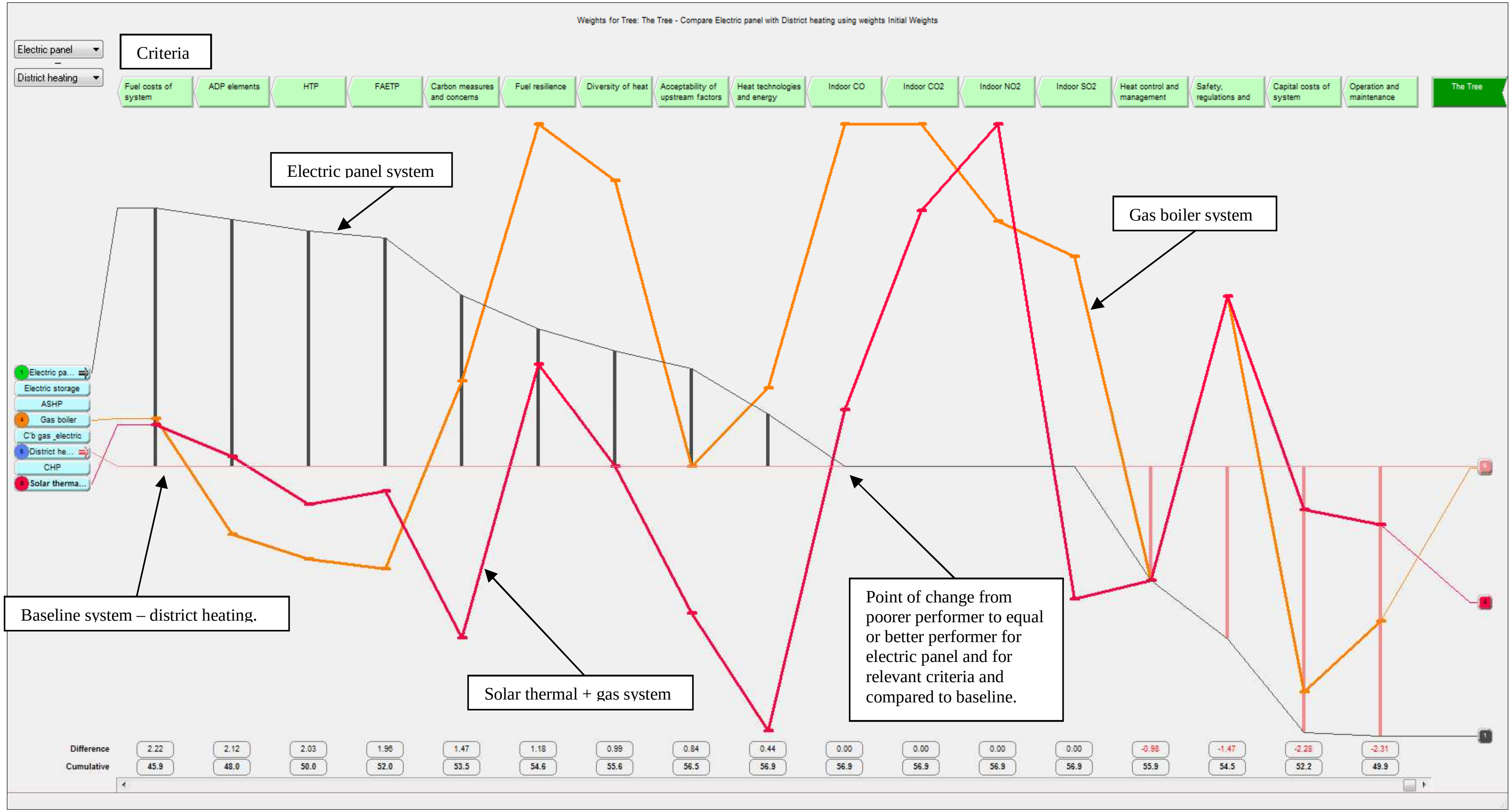


Figure 150 Robustness comparison of electric panel and district heating systems for all criteria (part two).

[The baseline system is district heating and compared to the electric panel system. The solar thermal + gas, and ASHP system are included for comparison].

7.5 Summary

This chapter has used MCDA to illustrate how the sustainability criteria can be aggregated into a single ranking score to facilitate decision making. The main findings are as follows:

- When equal weightings are applied to the environmental, economic and social criteria, the district heating system is the best option according to all three criteria.
- The CHP and combined solar and gas systems also perform well closely matching that of the district heating system. However, the CHP system has high capital and O&M costs and heat control and management issues. The combined solar and gas system ranks lower due to indoor air quality issues, safety and regulations and support to technologies.
- The electric based systems (panel, storage and ASHP) perform poorly particularly across the environmental and social indicators reflecting environmental concerns of electricity generation and householders' negative perceptions of electricity use for heating.
- Decarbonising the electricity mix does not change the ranking of the systems; however, the final performance results in the MCDA of the electric-based systems and community heat providing systems become closer.
- Finally, it is important to note that, assuming equal weighting the most sustainable systems are the larger community schemes requiring a certain number of households and demand to be economical and viable. By contrast, the individual systems which are often able to operate on minimum household numbers (panel, storage, gas boiler systems) tend to be less sustainable, particularly impacted through the environmental attributes.

The heat-providing systems considered in the multi-criteria decision analysis are now combined into scenarios for the period 2010 to 2050 at the national and urban levels – these are described further and studied in the next chapter.

8. Sustainability assessment of energy supply and demand mixes – future scenarios

8.1 Introduction

Following on from the multi-criteria decision analysis that considered the best sustainable solution to heat providing systems, this chapter discusses how those systems can be incorporated within different energy scenarios at the national and urban levels in the UK to assist in planning. Firstly, possible UK energy scenarios are identified and developed to provide the basis for the analysis. Secondly, the scenarios are evaluated on environmental, techno-economic and social sustainability. Finally, the results are analysed to determine the most sustainable scenarios at the national and urban levels. Prior to the above, the aim, objectives and approach to the study are discussed.

8.1.1 Aims and objectives

The goal of the Scenario Analysis (SA) is to:

a) Evaluate the environmental, techno-economic and social impacts of heat providing systems within selected scenarios;
b) Compare and contrast the sustainability of four scenarios at the national and two scenarios at the urban levels; and
c) Identify most sustainable scenarios using MCDA.

8.1.2 Assumptions and limitations

The following are the main assumptions and limitations of the study:

- This study focuses on domestic sector heat provision only. This includes space and hot water heating and cooking. Energy demand from lighting and appliances are not included directly in calculations.
- It is only possible to consider technologies for which full results have been compiled during the course of this research. This means that it has been necessary to simplify a number of heat providing systems as outlined in the Pathways scenarios by omitting or substituting the remaining technologies that contribute to the overall scenarios.

- Where common heat providing systems are considered such as district heating, CHP, combined gas and electric and combined solar the thermal systems – these are natural gas fuelled for the purposes of this study - biomass or other alternatives are not considered.
- Scenario costs are based on capital, operation and maintenance, decommissioning and disposal, and energy use over the scenario timeframe. However, for stages that have small or limited contribution to the costs, these have been omitted from the study.
- Replacement rates of household heat providing technologies is taken as 5% annually of the existing systems at the time (DECC, 2012a).
- Keeping in line with projected domestic demand data and the datum year of 2007 from the *Pathways calculator* for each scenario, the domestic demand shown for scenarios from 2010 differ accordingly.
- All scenarios except for the Reference scenario meet the Greenhouse gas emission reductions below 80% of the 1990 levels by 2050.

8.1.3 Methodology

The methodology used in this part of research is outlined in Figure 151. As shown, the following steps are involved:

- *Environmental sustainability assessment of heat-providing systems* - life cycle environmental impact data for the selected heat-providing systems are taken from Chapter 4 and includes: manufacture, installation, transportation, maintenance, dismantling, and disposal. Operational energy impacts are not included at this stage. In addition, indoor air quality data and the respective results are used.

- *Techno-economic and social sustainability assessment of heat-providing systems* – techno-economic and social criteria and results these are derived from the respective study chapters (Chapter 5 and Chapter 6) and used in the scenario development and analysis.

- *Pathways calculator* – the Pathways calculator is an experimental calculator where different ways of meeting the UK’s target to reduce emissions 80% by

2050 can be assessed by users (DECC, 2012a). The calculator contains a series of pathways based on real scientific data or other user pathways can be used for emissions. The calculator considers energy demand from industry, commercial domestic and the transport sectors. Supply considers electricity, gas, oil etc. Heat technology data from the Pathways calculator (DECC, 2012a) is used to assess the share and requirements of different heat systems and the domestic demand over the scenario timeframes. Life expectancy of each technology is derived from the original LCA study in chapter 4.

- *SPRIng scenario calculator* – the SPRIng scenario calculator is an integrated spreadsheet tool that enables the assessment of environmental impacts from electricity generation mixes (i.e. coal, wind, natural gas, coal CCS etc.) according to the user prescribed scenarios (SPRIng, 2011b). Electricity mix data from the ETLCA SPRIng scenario calculator is used to determine the electricity mix and grid emissions for the years 2010 to 2050 according to the selected scenarios and demand profile.

- *Integrated analysis* – an analysis spread sheet provides the framework and model for scenario life cycle impacts and overall assessment.

- *Scenario sustainability evaluation* – seven different scenarios are selected for assessment – these are described in the next section. Urban scenarios are developed and influenced from representative UK city energy scenarios and plans (BCC, 2005; CLASP, 2012; LEP, 2006).

- *Multi-criteria decision analysis* – multi-criteria decision analysis (MCDA) is used in the study to conduct sensitivity analysis on the environmental, techno-economic and social sustainability criteria for each of the scenarios. As in Chapter 7, the MCDA tool *Onbalance* (Quartzstar, 2010) is used for this assessment.

- *Results* – the results are used to assess the sustainability of the different scenarios, which assume different mixes of the heat-providing technologies and energy supply mix assessed.

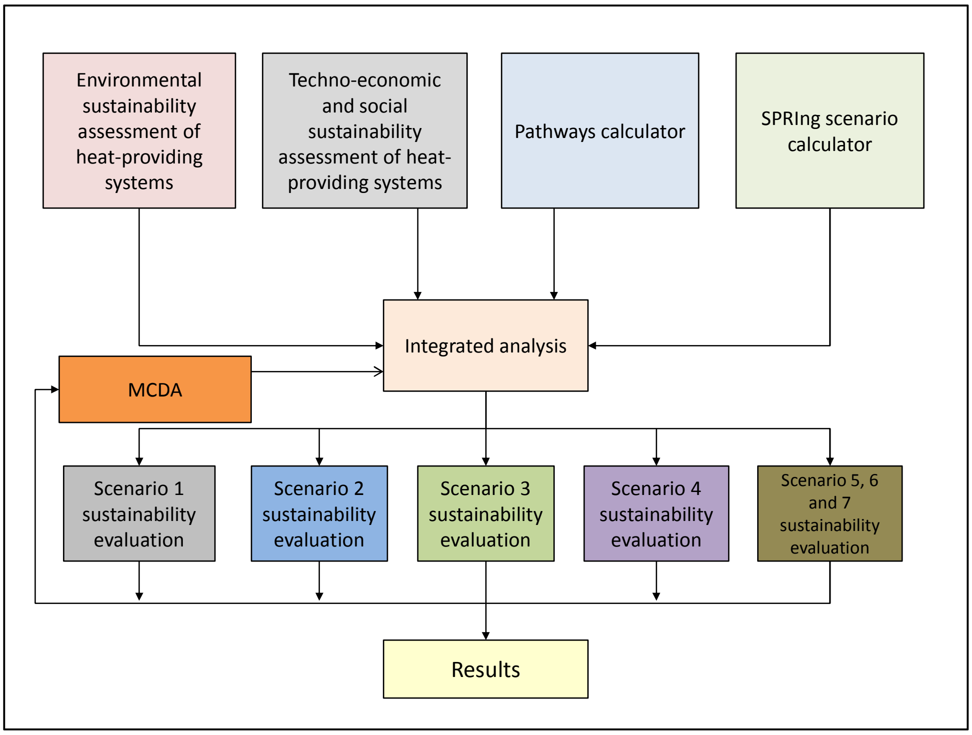


Figure 151 Scenario development process flow diagram.

8.2 Description of selected scenarios

For this study, three national level scenarios have been developed and compared with a reference scenario reflecting present day conditions. In addition, a further two urban focussed scenarios were studied to compare feasible urban heat-providing systems and futures related to the dynamics of urban domestic energy demand. All scenarios cover the period from 2010-2050. The four national level scenarios are:

Reference – national – considers a business as usual approach missing the target of 80% reduction of GHG over 1990 levels and relying predominately on natural gas for domestic heating – the scenario emulates that of 'doesn't tackle climate change' model in the Pathways calculator (DECC, 2012a). The Reference scenario was selected to provide a comparative baseline for the other scenarios based on a continuation of 'todays' condition.

High Electricity – reflects a high degree of electrification of heat especially through the use of heat pumps and electrical resistance heaters. The scenario builds upon the 'Higher renewables, more energy efficiency' model of the Pathways calculator. This scenario was selected to provide a view of the supply and demand requirements and impacts to support the electrification of heat nationwide.

National Grid – establishes a more moderate approach to the electrification of heat along with the continued but decreasing use of gas boilers. The scenario draws on the National Grid model in the Pathways calculator and National Grid future energy scenarios (NationalGrid, 2011). Selection of this scenario was to reflect a more gradual change of heat-providing technologies and accompanying energy supply adjustment than would be experienced through a rapid electrification of heat.

Markal – based on a scenario analogous to Markal 3.26 and described in the Pathways calculator. The scenario defines a common approach to household heating through district heating systems and the use of heat pumps. This scenario was selected as emphasis is placed on community based heat-providing systems including district heating.

The three urban level scenarios are:

Reference – urban – considers a business as usual approach to city energy provision between 2010 and 2050. The scenario does not tackle climate change but provides a comparative baseline for the Urban One and Urban Two scenarios.

Urban One – this scenario only considers cities and studies a major move toward domestic electrification of heat from 2010 to 2050 through heat pumps and resistance type heaters. This scenario differs from the national level scenarios as it focuses particularly on heat-technologies that are considered appropriate for the city situation (Air source heat pumps, storage heaters and panel heaters – see chapter 4) and reflects the population and growth of the 20 most populated cities in England.

Urban Two – this scenario again only considers cities and contemplates a change in domestic heating provision using community based systems and approaches particularly district heating and CHP. As for urban one scenario, population estimates reflect the 20 most populated cities of England.

The domestic energy demand profile according to each scenario is shown in Table 45. The Reference – national and urban follow the same profile. Data again is drawn from the Pathways calculator for each national scenario based on population and future estimated growth. Further, the Urban One and Two population and household data is calculated using the city data outlined previously in Chapter 4 and 23 Appendix 13. The technology mix for each of the studied scenarios during the timeframe is shown in Figure 152. For the national scenarios this is generally based on data from the Pathways calculator modelling the heat provision changes over the period according to the characteristics of each scenario. Urban One and Two scenario technology mixes are selected according to the progressive change of the scenario – Urban One considers electrification of heat through heat pumps etc. - Urban Two, the centralisation of heat-providing technologies through district heating and CHP by 2050.

The electricity supply mix used is largely outlined by each national scenario within Pathways calculator and then applied to the SPRIng calculator to estimate the LCA impacts. The electricity generation and gas combustion LCA impacts are shown in 24 Appendix 14. The electricity generating technology mix for each scenario is shown in 25 Appendix 15.

The Reference – Urban is taken as per Reference - National scenario. Urban One electricity mix is taken as per the national level High electricity scenario electricity mix. The energy demand profile is based on the 20 cities demand. The Urban Two electricity mix follows the Markal scenario electricity mix – and the demand profile is the same as the Urban One demand. Each of the studied scenarios is described in more detail in the next sections, presenting the electricity mix and demand profiles.

Table 45 UK domestic energy demand profile.

(TWh/yr)	Reference - national	High electricity	National Grid	Markal	Reference - urban	Urban One	Urban Two
2010	504	454	480	457	8.92	8.1	8.1
2015	525	405	458	415	8.92	7.0	7.0
2020	555	365	447	384	8.93	6.2	6.2
2025	584	337	441	358	9.05	5.5	5.5
2030	612	309	433	332	9.16	5.0	5.0
2035	629	285	431	310	9.3	4.6	4.6
2040	647	264	430	289	9.5	4.2	4.2
2045	667	247	432	272	9.7	3.9	3.9
2050	690	232	436	256	9.88	3.7	3.7

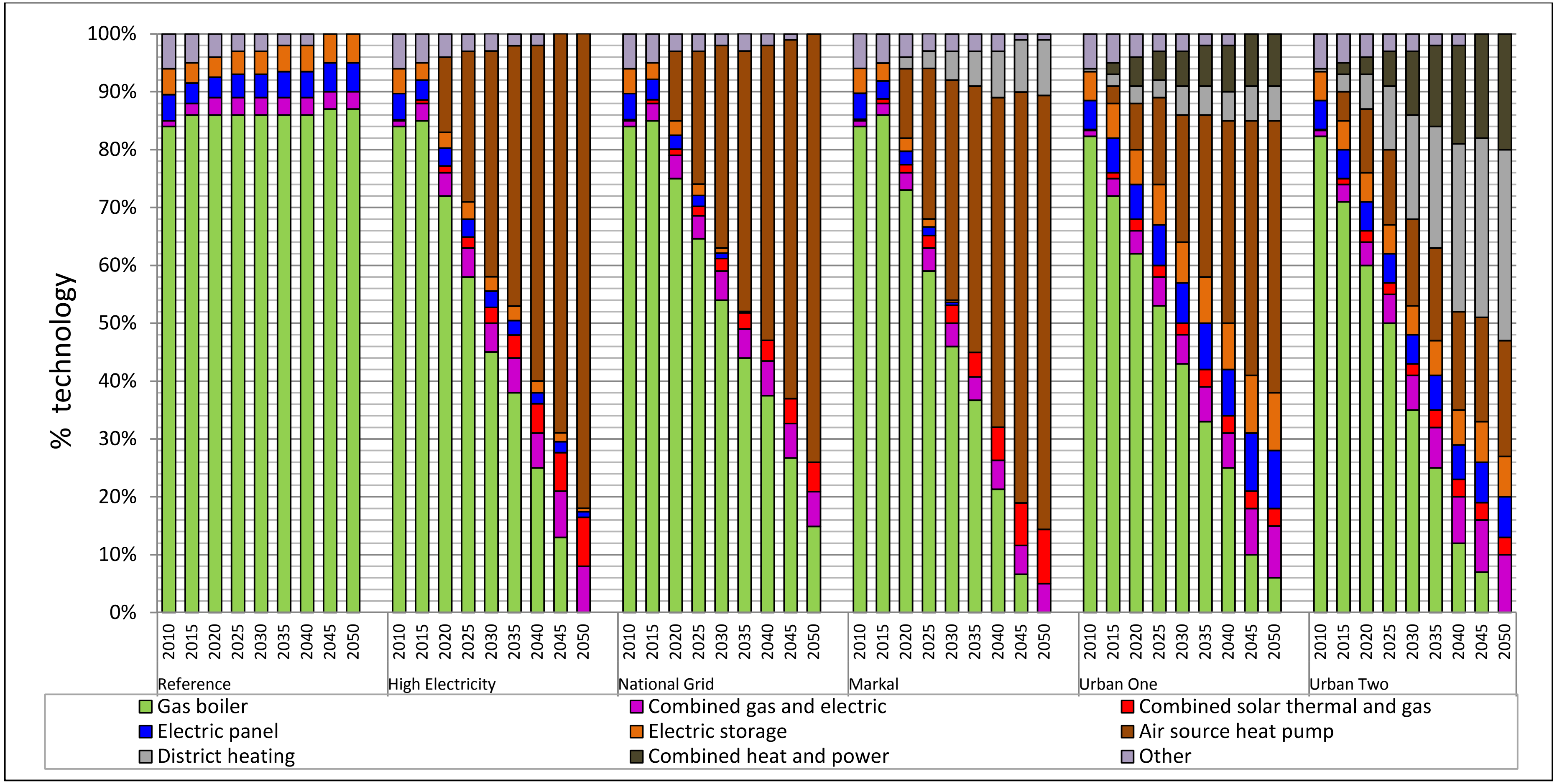


Figure 152 Percentage of technology within each of the studied scenarios and considered over the scenario timeframe of 2010 to 2050.

[Reference-Urban follows the Reference technology mix. 'Other' refers to solid fuel, oil etc].

8.2.1 Reference – national scenario

This scenario emulates the present conditions and that does not tackle climate change. Carbon emissions from electricity generation are expected to increase from 194 Mt CO_2 eq. per year to 211 Mt CO_2 eq. per year (DECC, 2012a). There is a decrease in overall domestic energy demand per household owing to improved insulation; nevertheless, electricity use increases and the natural gas remains the main energy source for domestic heating, particularly through individual gas boilers. This scenario is based on the Reference scenario of the Pathways calculator.

8.2.1.1 Electricity supply

There is little or no focus on decarbonising the electricity mix through use of renewables such as solar, wind or wave; the use of unproven low-carbon technologies such as wave power are not implemented to any scale. Wind turbines are not replaced after the end of their lifetime while carbon capture and storage (CCS) is still at its infancy by 2050 and then only applied to coal and biomass. Gas CCS is not implemented by 2050 due to capacity constraints associated with the gas and oil industries (GlobalCCS, 2012). However, natural gas provides the bulk of electricity supply through closed and open cycle gas turbine power stations while the undersea interconnector with France, Netherlands and Ireland (OFGEM, 2013) and other electricity imports are only used for balancing. Figure 153 provides an overview of electricity generation mix covering the scenario timeframe 2010 to 2050.

8.2.1.2 Domestic energy demand

Natural gas continues to play an important role in the supply of heat to more than 90% of UK homes and domestic cooking. There is little attempt at new electrification of heat with resistive heat technologies remaining at 10% only and natural gas is not decarbonised through increased use of biogas to any extent or at all. By 2050 homes have an average room temperature of $20^{o}C$, an increase from today's $18.4^{o}C$. (DECC, 2012a; Kane et al., 2011). Of the total homes in 2050, over 7m are insulated, while energy demand for domestic lighting and appliances increases by 20% relative to 2007 (DECC, 2012a). Figure 154 shows the scale of demand changes over the scenario period.

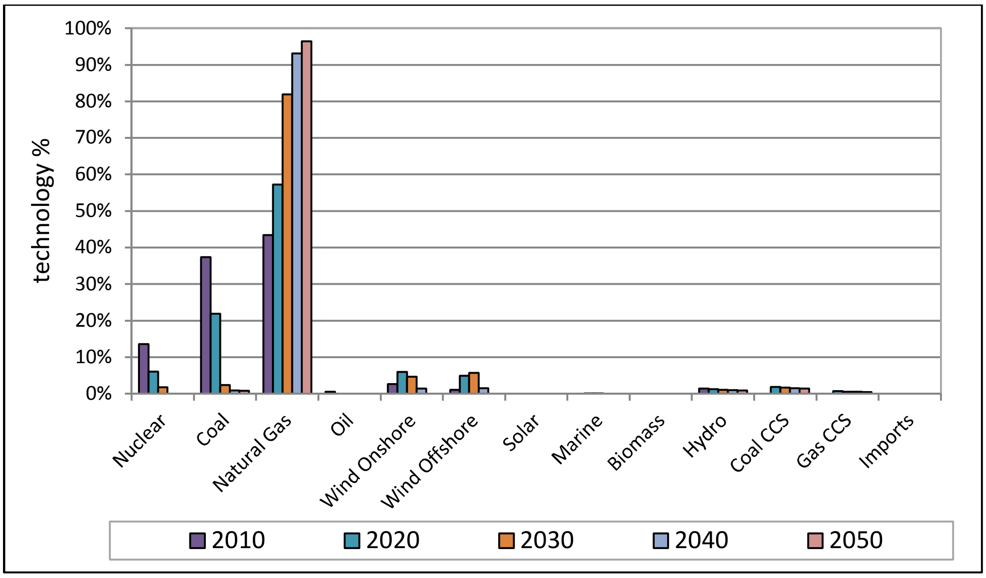


Figure 153 Reference scenario technology mix for UK electricity supply 2010 – 2050.

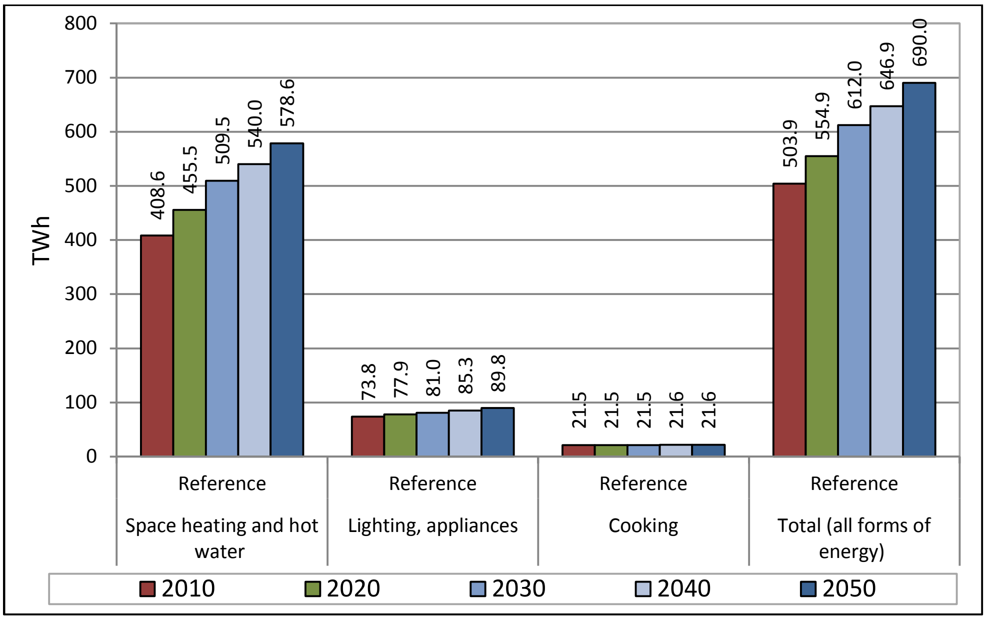


Figure 154 Reference scenario domestic energy demand 2010 – 2050.

8.2.2 High electricity scenario

This scenario discussed in DECC's Carbon Plan (HMGOV, 2011) views the future from the perspective of electrification based on the 'high electricity' scenario from the Pathways calculator. The pathways calculator, using data from the Carbon plan includes a future with a higher % of renewables and more energy efficiency. Overall it presents a major reduction in renewable costs and is based on a step change in per capita energy demand reduction while featuring an expansion in electricity storage capacity (DECC, 2012a).

8.2.2.1 Electricity supply

The high electricity scenario for electricity supply is predominately fed with wind generated electricity providing over 55% of the total electricity supply (DECC, 2012a). Other renewables, as seen in Figure 155 supply moderate levels of electricity, however base load power is essentially supplied from nuclear and ultimately coal and gas CCS. The electrification of heat especially, and the substantial deployment of intermittent generation are likely to make it harder for supply to follow demand (ERPT, 2011); here though 20 GW of pumped storage provides extra storage capacity in this respect and gas back up may assist service during any lull in wind generation. Gas provides a declining role over the scenario period with an emphasis on energy independence (DECC, 2013b). Bioenergy is harvested from approximately 25,000 km^2 of land area in the UK and other countries (DECC, 2012a). Local air quality is likely to be improved in this scenario with reductions in particulate matter and emphasis on renewables – reductions could be around 60-85% lower in 2050 compared to 2010 (DECC, 2012a).

8.2.2.2 Domestic energy demand

The high electricity scenario for domestic energy demand shows a progressive reduction in space and water heating demand over the scenario timeframe – see Figure 158. Emphasis is given to energy efficiency improvement through both cavity and solid wall insulation. Domestic heating demand is met primarily through house level electrified heating systems (DECC, 2012a); behavioural changes and smart controls lower average house temperatures.

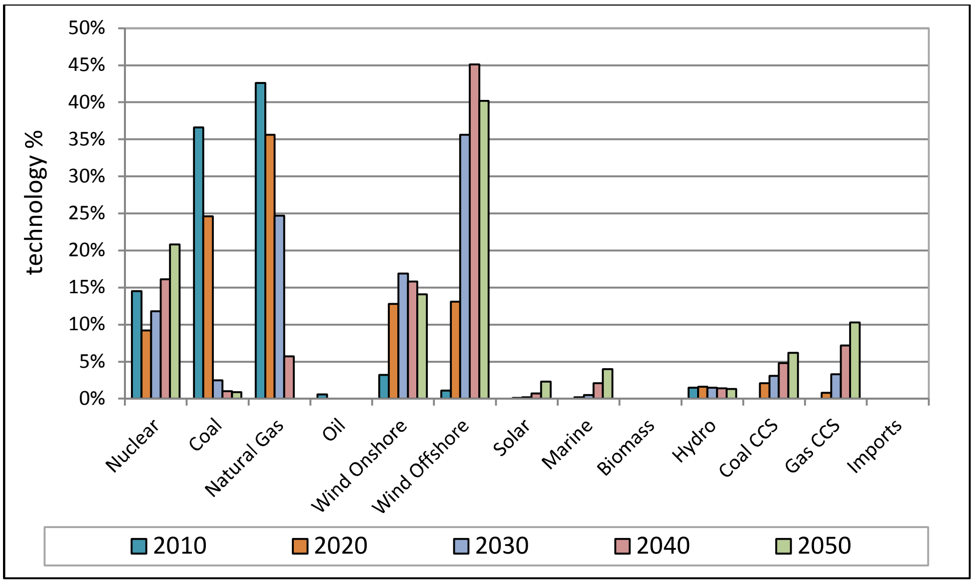


Figure 155 High electricity scenario technology mix for UK electricity supply 2010 – 2050.

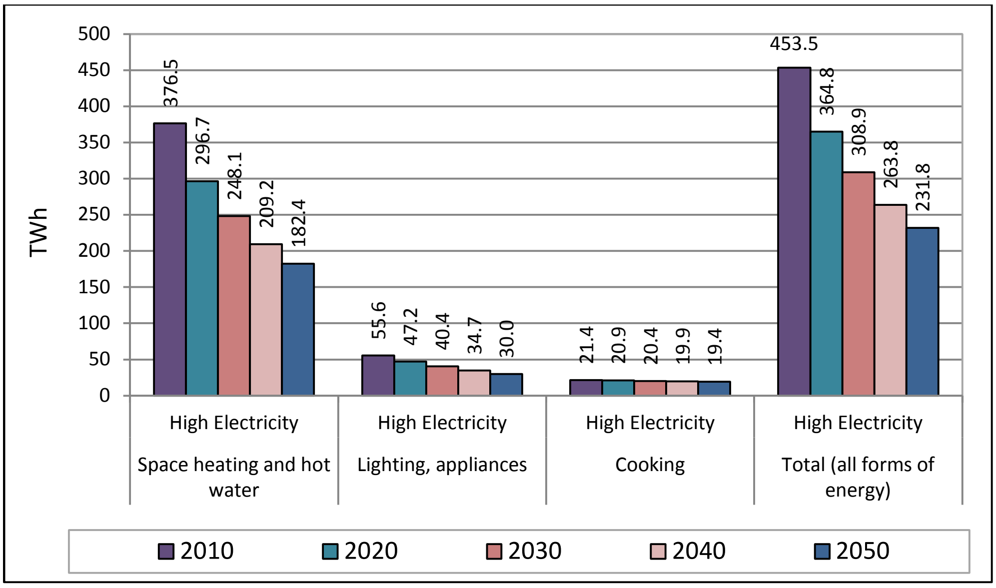


Figure 156 High electricity scenario domestic energy demand 2010 – 2050.

8.2.3 National Grid scenario

This National Grid scenario is based on the balanced pathway grouping and provides an insight into the growth of electricity particularly for heat but in addition, the electrification of transport (Rimmer, 2012a). Five pillars are exploited within the scenario, demand efficiency, renewables, nuclear, CCS and flexible interconnected networks (Rimmer, 2012b).

8.2.3.1 Electricity supply

The National Grid balanced scenario provides for decarbonised electricity generation and supply through the use of wind, other renewables, nuclear and CSS – see Figure 157. Its interconnection with other European networks provides a flexible approach to electricity delivery. Emphasis is given to affordable solutions based on economies of scale and deliverability; although having contributions from most sectors none are maxed-out. This approach is said to be balanced, supporting sustainability, security of supply and consumer energy variations and possibly reflecting the expertise and experience of the electricity supply and transmission industry.

8.2.3.2 Domestic energy demand

Domestic energy demand is principally based on the supply of electricity for heating supported by significant improvement to insulation and overall energy efficiency – see Figure 158. Where this proves less effective duel fuel/hybrid systems are supported (DECC, 2012a). It is recognised that for space heating the annual heat demand the seasonal profile is steeper and more complex than that for lighting, appliances and cooking. As described in earlier chapters, this could result in the need for significant network investments, low load factor power stations and the enhancement of storage. To mitigate this, base-load heat would come from electricity, while seasonal heating over high demand periods is derived from the use of natural and replacement gas.

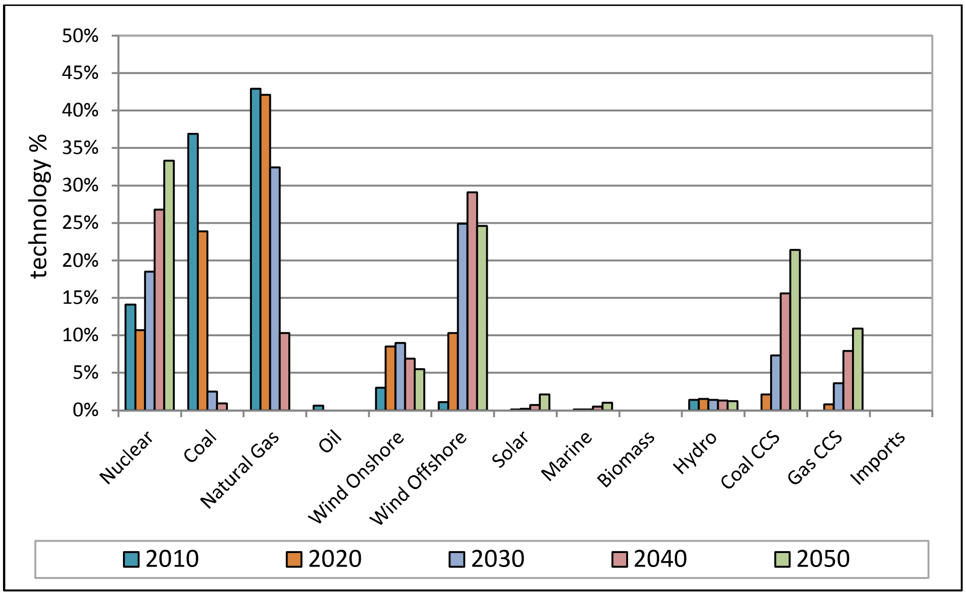


Figure 157 National Grid scenario technology mix for UK electricity supply 2010 – 2050.

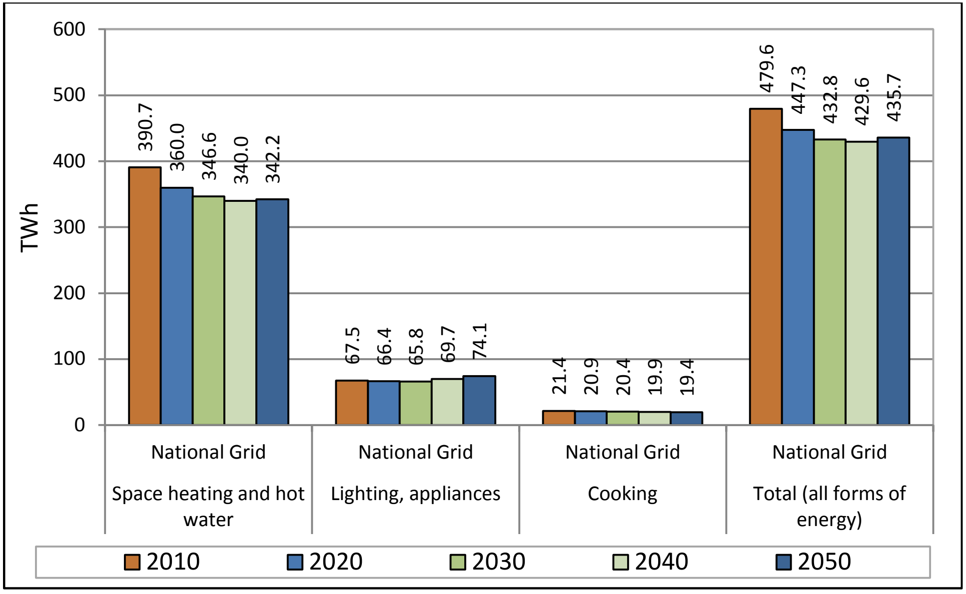


Figure 158 National Grid scenario domestic energy demand 2010 – 2050.

8.2.4 Markal analogous 3.26 scenario

The Markal 3.26 is recognised and used within the governments carbon plan (HMGOV, 2011) and is a peer reviewed modal used to model national energy system change over the medium and long term. The Markal 3.26 is included in the Pathways calculator (DECC, 2012a) as a scenario for future energy impact analysis.

8.2.4.1 Electricity supply

The Markal scenario demonstrates the increased use of nuclear power in the electricity generation mix; increasing from 12% to 42% across the scenario timeframe. There is less emphasis on wind generation but key contributions from marine at nearly 10% by 2050 and more importantly, the substantial use of CCS for both coal (20.3%) and gas (10.4%) by the end of the scenario term – see Figure 159.

8.2.4.2 Domestic energy demand

Domestic energy demand for the Markal scenario again reflects a substantial decrease in demand for space and water heating and moderate declines in lighting and appliances energy use while cooking becomes entirely electric by 2050 – see Figure 160. The achievement of these reductions is through a decrease in room temperatures to 16^{o}C (DECC, 2012a); greater than 18 million homes insulated and energy saving efficiencies for lighting and appliances. In addition, greater use is made of district heating systems in this scenario for heat provision although Markal assumes this will be derived from power stations; here in this study, it is sourced from local energy plants.

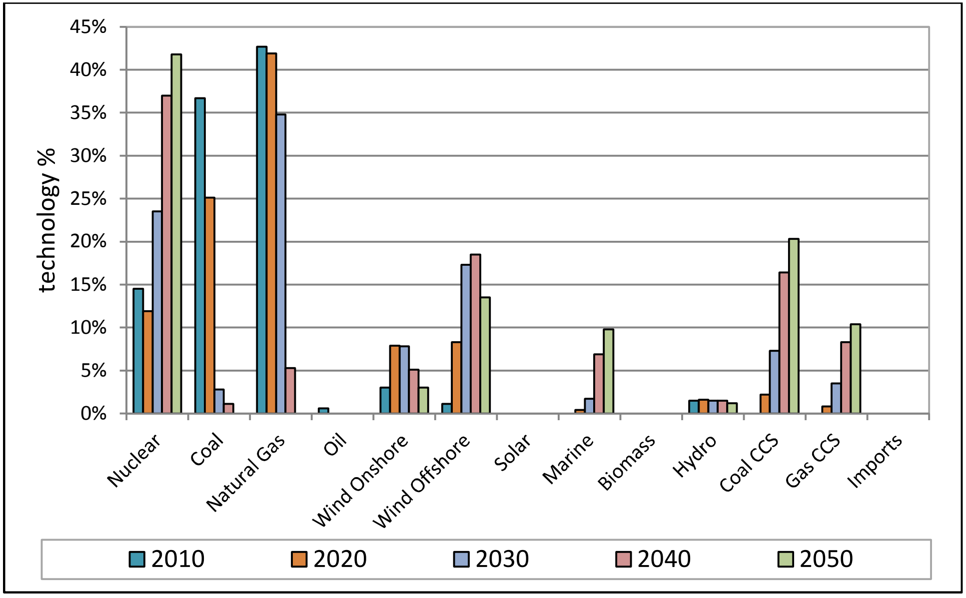


Figure 159 Markal 3.26 Scenario technology mix for UK electricity supply 2010 – 2050.

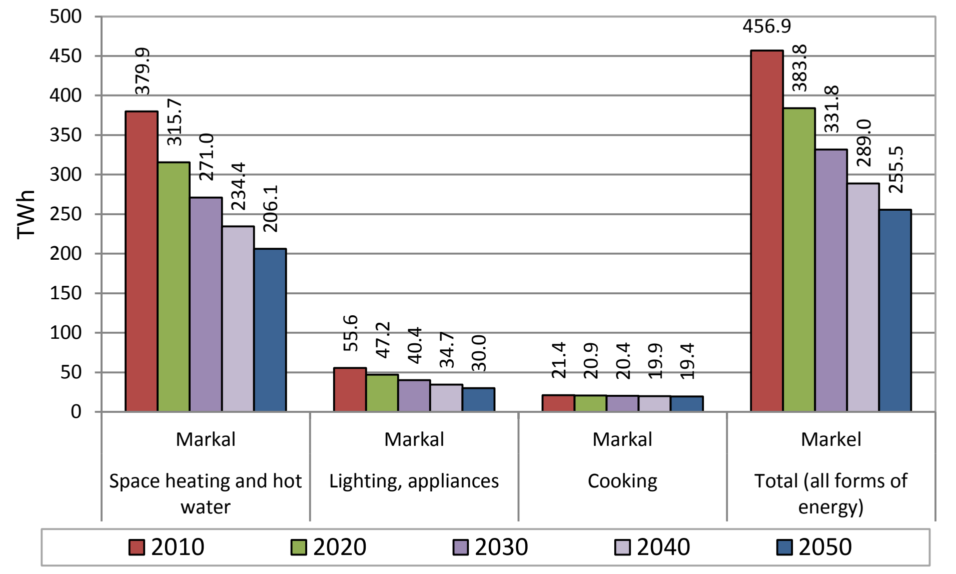


Figure 160 Markal 3.26 scenario domestic energy demand 2010 – 2050.

8.2.5 Reference – Urban scenario

This scenario is very similar to the Reference – national scenario. It does not tackle climate change and carbon emissions from electricity generation are expected to increase through the growth in natural gas fuelled electricity generation using open and closed cycle gas turbines. In addition, there is a decline in renewable generation especially on and offshore wind – nuclear generation also declines between 2010 and 2050. The main fuel continued to be used in city households is natural gas - there is a decrease in overall domestic energy demand per household owing to improved insulation; nevertheless, electricity use increases. This scenario is principally based on the Reference scenario of the Pathways calculator.

8.2.5.1 Electricity supply

The electricity supply mix in this scenario is as described previously for the Reference – national scenario – refer to Figure 153.

8.2.5.2 Domestic energy demand

Figure 4 shows the scale of demand changes over the scenario period. Overall demand increases due increasing population in cities. Natural gas continues to play an important role in the supply of heat to more than 90% of city homes and domestic cooking. There is an increase in combined gas and electric heat-proving systems and common supplied systems such as gas fuelled centralised heat systems. There is little attempt at new electrification of heat with resistive heat technologies remaining at 10% approximately.

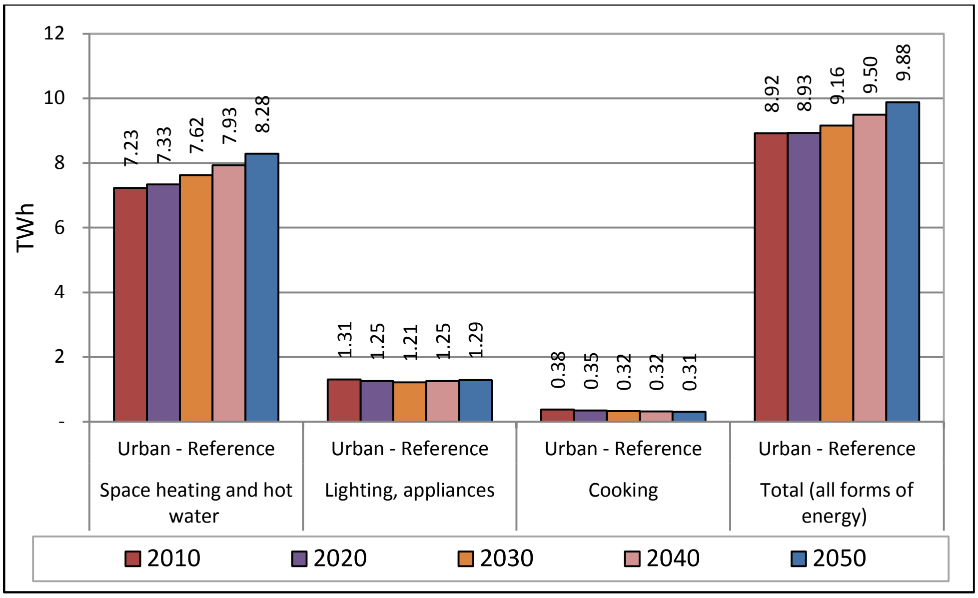


Figure 161 Reference – Urban scenario domestic energy demand 2010 – 2050.

8.2.6 Urban One scenario

This scenario considers impacts relating to an urban energy future principally based on the electrification of heat between 2010 and 2050 and only considering cities. Importance is placed on the electric sources of heat and the gradual withdrawal of individual gas to homes although not completely. Further heating is supplied through combined systems and decentralised supplies including district and CHP systems. The scenario considers typical city domestic heat and electricity demands based principally in dense housing such as apartment blocks, terraced streets and other housing accommodating higher density living.

8.2.6.1 Electricity supply

The Urban One electricity supply scenario reflects a decarbonised generation predominately using onshore and offshore wind, other renewables, and nuclear; towards the end of the scenario CSS for both gas and coal is used. The scenario closely follows the high electricity scenario described earlier in 8.4.2.1. Nuclear power generates over 20% of supply by 2050 while direct natural gas and coal see dramatic reductions over the 40 years. Growing use of solar, marine and CSS for both coal and gas provide for the remaining generation – see Figure 162. This is the typical supply mix provided through the transmission systems to cities. However, decentralised power generation within the city is seen to expand during the scenario albeit slowly. Such decentralised generation could change the localised power contribution mix especially through the use of CHP, solar, and wind – this is included within the scenario.

8.2.6.2 Domestic energy demand

City housing domestic energy demand within the Urban One scenario reflects energy efficiency gains through house and apartment insulation and the installation and use of smart energy management control systems. Here, the electrification of heat through community ASHP and resistive heating has taken place providing over 67% of the required heat – see Figure 163. Demand for heat is supported through a smaller number of combined heat and power and district heating systems.

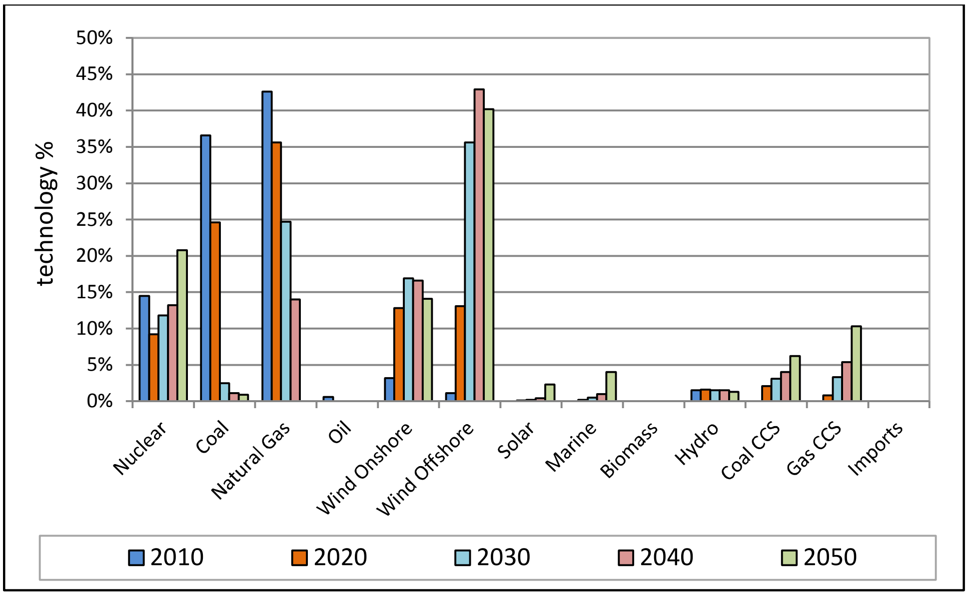


Figure 162 Urban One scenario technology mix for UK electricity supply 2010 – 2050.

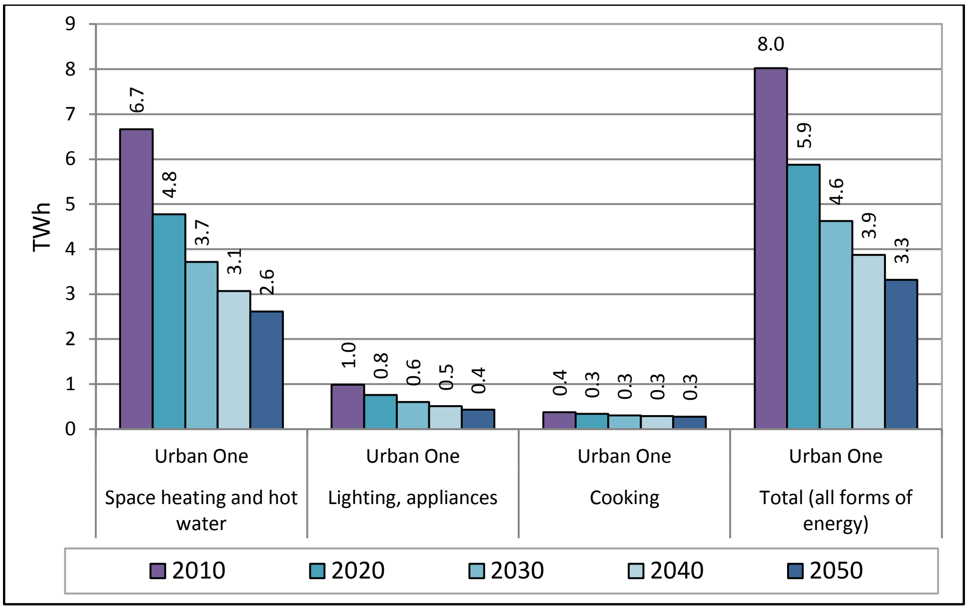


Figure 163 Urban One scenario domestic energy demand 2010 – 2050.

8.2.7 Urban Two scenario

This final scenario studies the impacts related to an urban energy situation in which greater emphasis is placed on decentralised heating such as district heating, CHP systems and centralised gas and only relates to cities. Other heating is supplied principally through electricity to ASHP and resistance type heating. Towards the end of the scenario timeframe individual gas boilers are phased out completely.

8.2.7.1 Electricity supply

The Urban Two scenario uses electricity generated from increased utilisation of nuclear power and following the same profile as seen for the Markal scenario – see Figure 159. There is key use of CCS in the latter years especially relating to coal and gas. Total generation is up from 75 GW in 2010 to 112 GW in 2050.

8.2.7.2 Domestic energy demand

City housing domestic energy demand within the Urban Two scenario is essentially based on that described in the Urban One scenario. Energy efficiency gains are made through insulation and overall building improvements while heating is provided to more than 60% of households as heat by 2050.

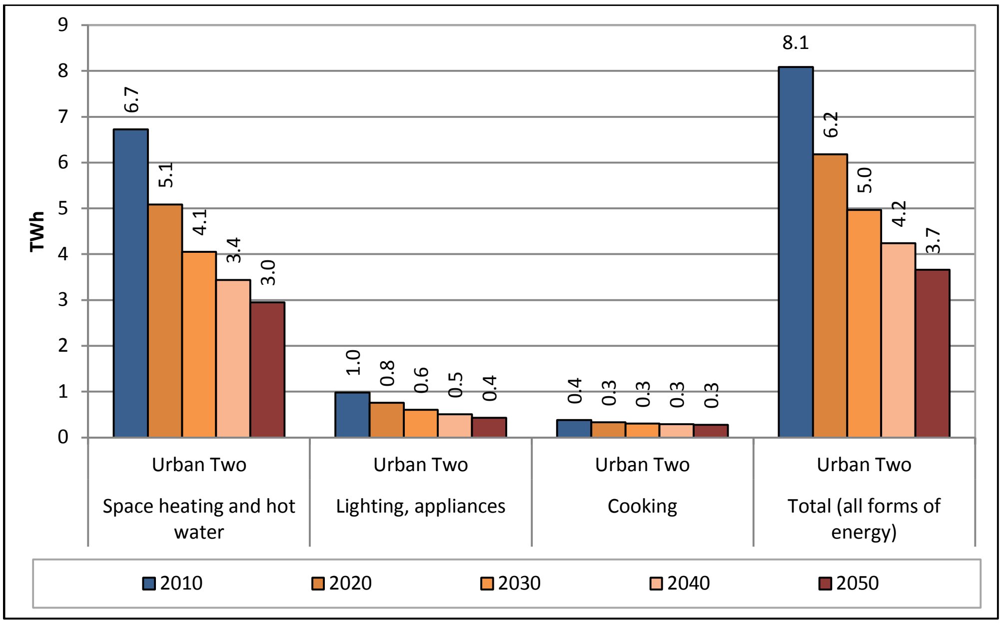


Figure 164 Urban Two scenario domestic energy demand 2010 – 2050.

8.3 Sustainability assessment of scenarios

This section discusses the results of the sustainability assessment of the three national and the reference scenarios for the years 2010 to 2050 and subsequently the two Urban based scenarios with the Reference-urban scenario covering the same period. The results are detailed below and are represented in Figure 165 for the national scenarios and Figure 166 for the Urban scenarios. In addition, the comparison between the 2010 impacts and those of 2050 are shown in Figure 167 for national and Figure 168 for the urban scenarios. ADP elements, ADP fossil and HTP are discussed here but are ultimately included within the social sustainability section. Impacts are cumulative unless otherwise stated. Finally, Figure 169 and Figure 170 show impacts per kWh of heat delivered for each of the scenarios.

8.3.1 Environmental sustainability assessment

ADP elements: ADP elements are lower overall in the Reference scenario, with an emission rate of 159,596 tonnes Sb eq. compared to the other three national scenarios which are very similar in overall impacts at just over 204,000 tonnes Sb eq. This is due to the lower depletion of elements in the gas boiler systems that are extensively used in the Reference scenario compared to the ASHP that is predominately used in the High electricity, National Grid and Markal scenarios. Over the scenario period, the Reference scenario shows only a 58% increase on 2010 impacts while the other scenarios grow by 158%. Depletion of elements correlates to the construction and implementation of renewable electricity plant – all scenarios except the Reference are renewable intensive. These plants have high metal requirements compared to the Reference scenario. All scenarios show increases from 2010 to 2050.

The Urban One and Two scenarios have very similar overall ADP element impacts to each other; however the Urban One final depletion of elements in 2050 is 7% higher than the Urban Two scenario at 2,990 tonnes Sb eq. The Reference – urban scenario has the lowest ADP – elements overall at 2,465 tonnes Sb eq. over the 40 years. As described for the national scenarios, the high metal usage of the Urban One and Two scenarios is the main contributor to these impacts. In the Reference – urban, the rise is due to increasing household numbers.

ADP fossil: the Reference scenario shows a growth of 37 % from 2,151,700 TJ to 3,133,000 TJ ADP fossil between 2010 and 2050; the National Grid scenario shows a 8.4 % growth while the High electricity and Markal scenarios exhibit moderate declines for the same period. The growth in the Reference scenario is through the use of a heavily carbonised electricity mix particularly the growth of natural gas for power generation. The National Grid electricity mix; although placing more emphasis on decarbonisation, still exhibits a relatively poor mix using natural gas until relatively late in the scenario.

Urban One has a lower overall ADP fossil depletion than the Urban Two scenario; however both scenarios show a reduction of approximately 35% over the 40 year period. The Reference – urban have the highest ADP fossil and increases over the scenario duration – this is due to the growth of natural gas and overall demand.

AP: overall, all scenario AP impact levels are similar only ranging from 19.6 Mt SO_2 eq. to 22.4 Mt SO_2 eq. However, between 2010 and 2050 the Reference scenario shows only a moderate increase from 0.542 Mt to 0.566 Mt SO_2 eq. All other scenarios except the Reference show notable increases in AP impacts mainly through a slight increase in the use of coal in the electricity mix but directly and increasingly through coal CCS.

The Urban Two scenario provides higher AP impacts than Urban One and again both scenarios experience an increase of 11% when the years 2010 and 2050 are compared. The same applies to the Reference - urban scenario however a reduction of 16% is observed – this is mainly due to the reduction in the use of coal in power generation over the period.

EP: in a similar manner to the AP indicator, final overall results are moderately similar for all scenarios with the Reference scenario the lowest and the National Grid scenario the highest. The Reference scenario shows only a 13% increase and the National Grid scenario an 88% increase in Eutrophication from 2010 to 2050; the High electricity and Markal scenarios show similar sized increases. The increase is due to the growing use of electricity for heat provision.

A similar pattern is seen for the Urban One and Urban Two scenarios where increasing use of electricity within the scenarios feature as increases in EP. Nevertheless, the Urban Two scenario shows the higher overall EP impact 50,000 tonnes PO4 eq. overall and the Reference – urban the lowest at 41,600 PO4 eq. cumulative.

FAETP: overall FAETP impacts are lowest for the Reference scenario at 98,000 Mt DCB eq. while the remaining three national scenarios exhibit similar higher impacts at 160,000 – 170,000 Mt DCB eq. This pattern is also seen in the contrast between 2010 and 2050 impacts with substantial increases for the latter three scenarios. The higher impacts are due to an increasing use of nuclear power during the High electricity, National Grid and Markal scenario compared to the present day based Reference scenario but also the impacts from wind, coal and solar based technologies that offer high FAETP impacts than today's natural gas.

Urban One and Two show large increases across the scenarios with Urban Two higher overall and in 2050 compared to 2010. Although this scenario does not contain substantial electrification of heat element it does reflect FAETP impacts through the large use of CHP sourced district heating. The Reference – Urban offers the lowest FAETP impacts at 15 Mt DCB eq.

GWP: as shown in Figure 165, the GWP of the High Electricity scenario is the lowest and the Reference scenario the highest. This correlates to the increased use of renewables – especially onshore and off shore wind generation. Nuclear electricity generation also increases between 2010 and 2050 offering low GWP. For all scenarios, GWP reduces over the 40 year period except for the Reference scenario. The GWP of the High Electricity scenario reduces from an estimated 161 Mt CO_2 eq. in 2010 to 119 Mt CO_2 eq. in 2050, a reduction of 26%; this is due to a reduction in domestic demand over the period.

Urban One and Two scenarios have practically the same overall GWP emissions (88 Mt and 97 Mt CO_2 eq. respectively) with the final year 2050 emission 10% higher for the Urban Two scenario. The lower impacts of the Urban One scenario reflect the decreasing GWP of the electricity mix and this also experienced in Urban Two where 34% of heat is from electricity by 2050. The Reference-urban scenario has the highest overall emissions (127 Mt CO_2 eq.) and shows an increase in emissions between 2010 and 2050 – this is due to increasing number of households and high carbonised electricity supply.

HTP: increases in HTP are shown across all scenarios between 2010 and 2050; these being sizable for the High electricity, National Grid and Markal scenarios at 410%, 380% and 415% respectively – the Reference only increases by 54%. Overall impacts of High Electricity - 8,700 Mt DCB eq. National Grid - 7,900 Mt DCB eq. and Markal - 8,900 Mt DCB eq. are dominant compared to the Reference scenario at 4,200 Mt DCB eq. This is due to the higher use of electricity in the scenarios and particularly through the ASHP and wet systems for heat delivery.

Similar impacts are demonstrated in the Urban One and Urban Two scenarios with the latter showing moderately higher impacts overall. The Reference – Urban has the lowest overall HTP and shows only a small increase over the scenario.

MAETP: the largest increase between 2010 and 2050 is experienced by the National Grid scenario and shows a growth of 292%. This difference is mainly due to aerial emissions during the operational stages but particularly coal CCS that features in this scenario. In contrast, the best scenario is the Reference-national emitting overall 1,921,000 Mt DCB eq.

As expected, the Urban Two scenario has the higher overall MAETP impacts at 46,000 Mt DCB eq. and shows increases from 2010 to 2050 – this reflects its greater use of coal CCS in the generation mix.

ODP: higher in all scenarios, particularly the Reference – 1,750 tonnes R11 eq. and National Grid – 1,570 tonnes R11 eq. The higher ODP's are due to the higher ODP levels in the electricity mix and use of gas boiler systems for the Reference scenario and the combination of ASHP and gas boiler systems in the National Grid scenario – both demanding PTFE in their wet systems. All scenarios show increases between 2010 and 2050.

Contrary to the Reference – urban scenario, Urban One and Two both show decreasing ODP between 2010 and 2050 with Urban Two being the lower. Both scenarios have declining numbers of individual gas boiler systems.

POCP: in terms of POCP, the High electricity 2.4 Mt C_2H_4 eq. and Markal 2.5 Mt C_2H_4 eq. scenarios are the best options, although moderate increases are experienced for these and the remaining national scenarios from 2010 to 2050. The National Grid scenario shows the largest increase over the period at 38%. The Reference scenario has the highest overall POCP – 2.7 Mt C_2H_4 eq. showing the impacts of natural gas use as the main energy source.

A slight decrease in POCP is shown for the Urban One scenario - 1,031 to 1,029 tonnes C_2H_4 eq. whereas the Reference-Urban and Urban Two show increases between 2010 and 2050. This is due to the move from individual gas boilers in the Urban One scenario to heat pumps and resistance heating.

TETP: higher in all scenarios with substantial increases over the scenario for the High electrification, National Grid and Markal scenarios – the best option remaining the Reference scenario. By 2050, increases in the order of 570% relative to 2010 levels are observed - this result reflects on the increased use of electricity within the three former scenarios – especially through coal CCS, and heavy metal emissions in the nuclear life cycle.

As per the national scenarios, large increases are seen for both Urban One and Two scenarios with the latter the highest at 327 Mt DCB eq. Although contrary to the profile of the national scenarios, Urban Two's impacts relate to the growing use and construction impacts of the district heating systems.

Impacts per kWh

When consideration is given to the environmental impacts based on the kWh of heat delivered by each scenario and the heat-providing systems in each – a multifaceted picture emerges – see Figure 169 and Figure 170. The Reference-national and Reference-Urban show decreasing impacts by 14% per kWh across all indicators despite more gas being delivered, but a slightly greener electricity being generated. The other national and urban scenarios all show increases of between 250 and 430% – best performing in this respect is the National Grid scenario with its middle placed energy demand, continued use of some gas through boilers and more electricity used for heat. The worst performing is the high electricity and Urban One mainly through their high use of electricity for heat despite offering the lowest demand of the national and urban scenarios. The Reference scenarios all exhibit increasing demand between 2010 and 2050 whereas all others show decreasing demand despite population increases.

Life cycle impacts for GWP show a decrease for the Reference from 456 to 405 g CO_2 eq. per kWh. The largest increase between 2010 and 2050 is the High electricity at 430 to 723 g CO_2 eq. per kWh and the Urban Two scenario at 425 to 645 g CO_2 eq. per kWh.

Indoor air quality: - (Carbon monoxide, Carbon dioxide, Nitrogen Dioxide and Sulphur dioxide) – for each of the emissions shown Figure 171, the Reference scenario exhibits the highest values representing less preferred indications. The Reference scenario (shown as Reference for Reference-national and Reference-Urban), and to a lesser extent, the National Grid scenario use individual gas boilers and gas based cooking for an extensive period of time within the scenarios thus contributing to the increased values of CO, CO_2 and NO_2 and subsequently to poor indoor air quality (BRE, 2005c). Lower indoor emissions are seen as expected in the Urban Two scenario, and the Urban One scenario that is based on low carbon electricity emissions from generation and a high level of heat electrification particular all-electric cooking.

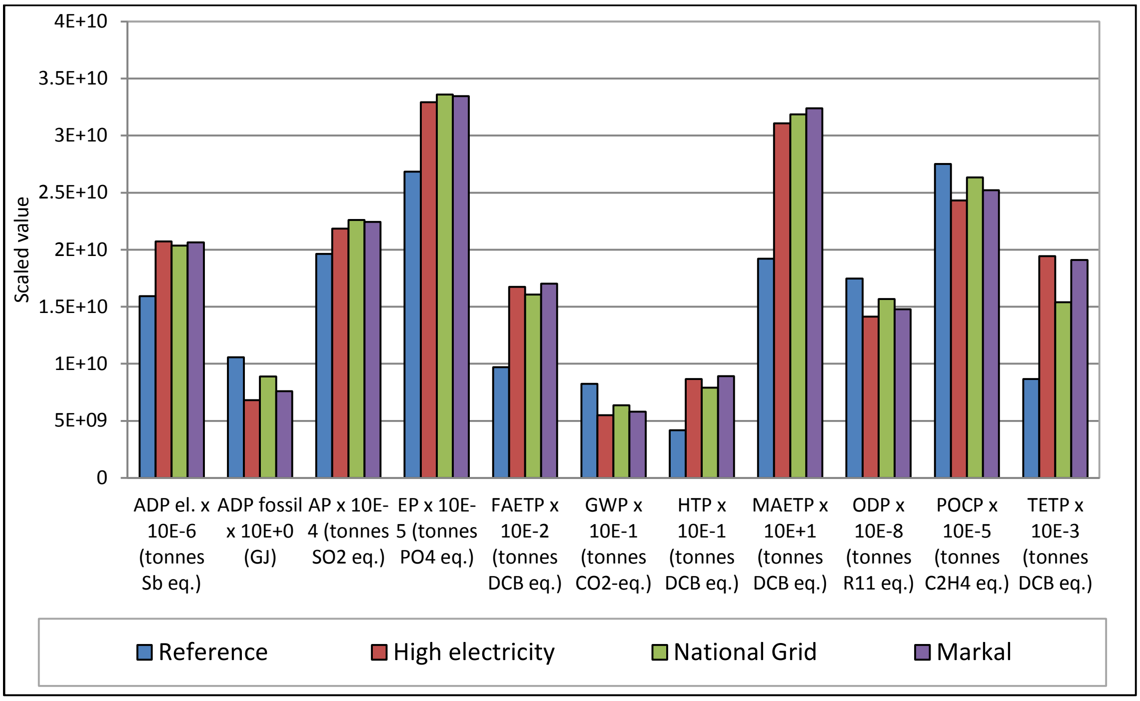


Figure 165 Environmental sustainability assessment of scenarios showing cumulative impacts for the years 2010 to 2050.

[ADP elements, ADP fossil and HTP indicators included here for completeness, however these indicators are also shown in the social section for each scenario].

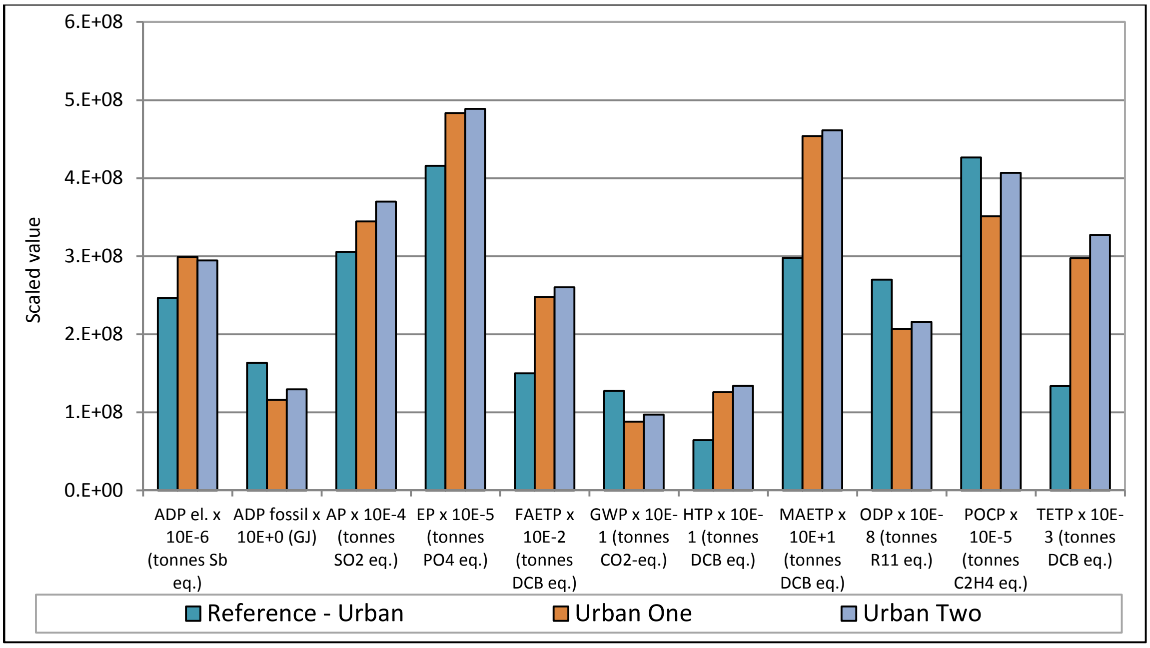


Figure 166 Comparative results for Urban One and Urban Two scenarios considering year 2010 to year 2050 impacts

[ADP elements, ADP fossil and HTP indicators included here for completeness, however these indicators are also shown in the social section for each scenario].

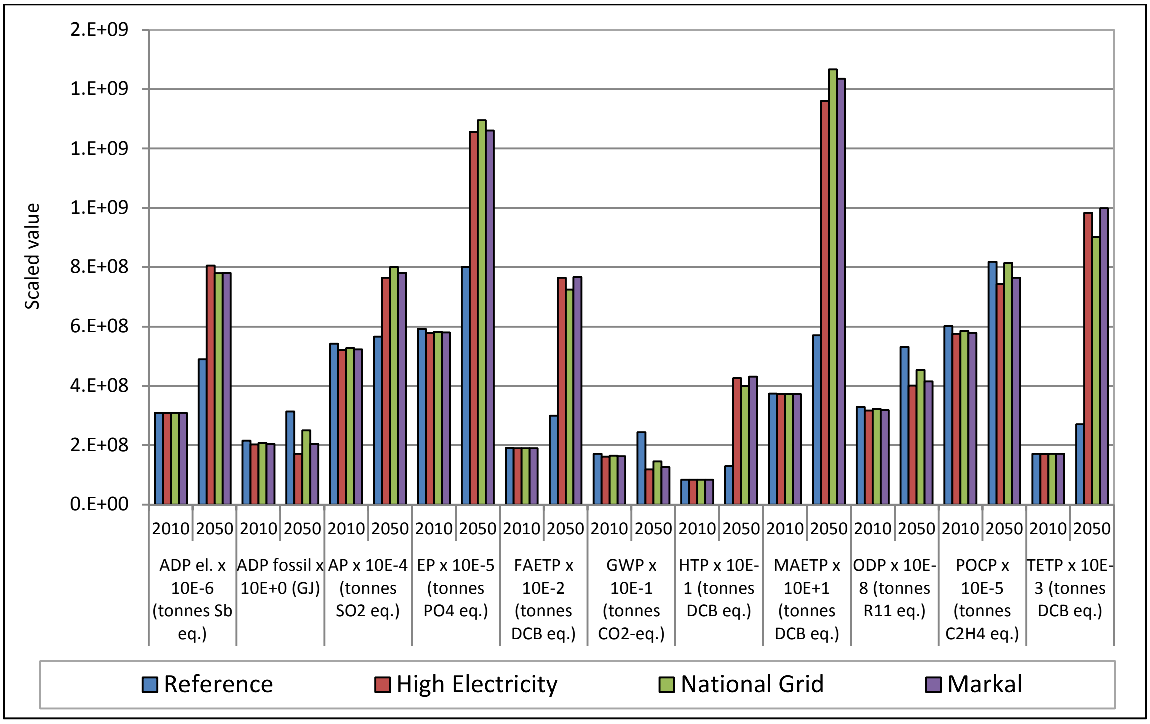


Figure 167 Comparative results of national scenarios considering year 2010 and 2050 impacts only.

[ADP elements, ADP fossil and HTP indicators included here for overall comparisons, however these indicators are also shown in the social section for each scenario].

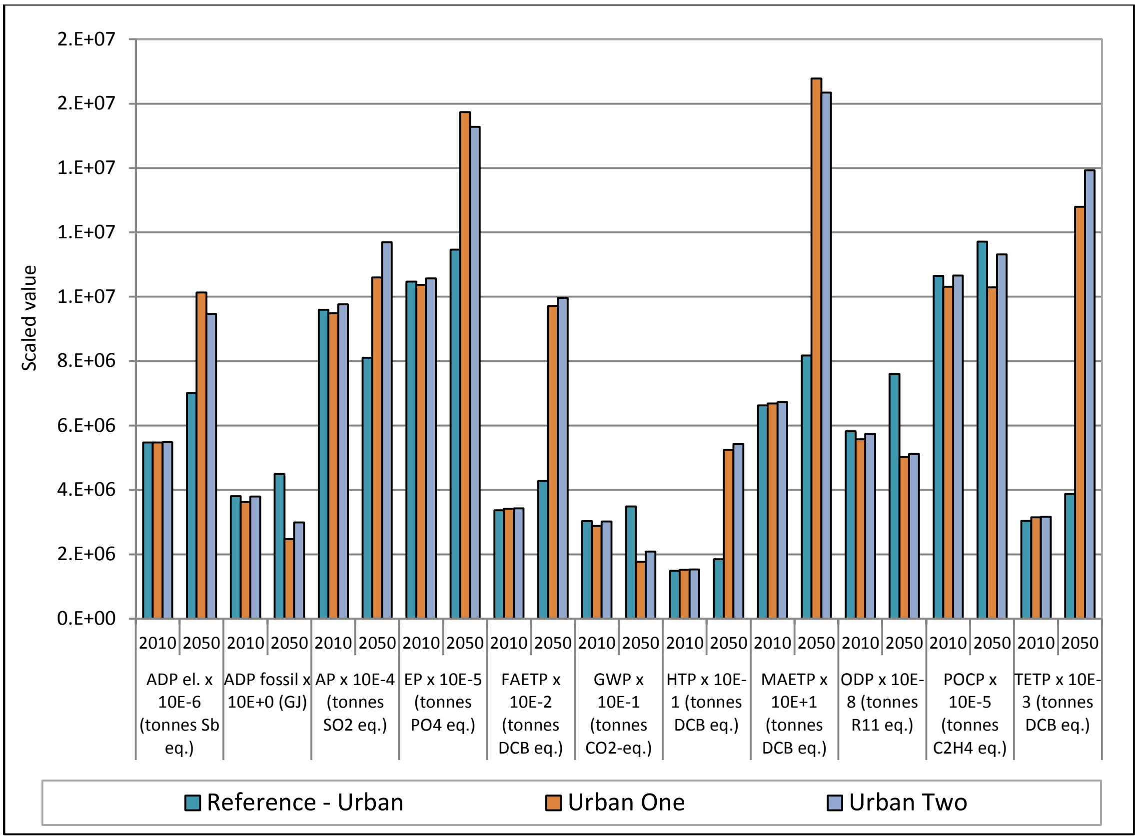


Figure 168 Comparative results for Reference – Urban, Urban One and Two considering year 2010 and 2050 impacts only.

[ADP elements, ADP fossil and HTP indicators included here for overall comparisons, however these indicators are also shown in the social section for each scenario].

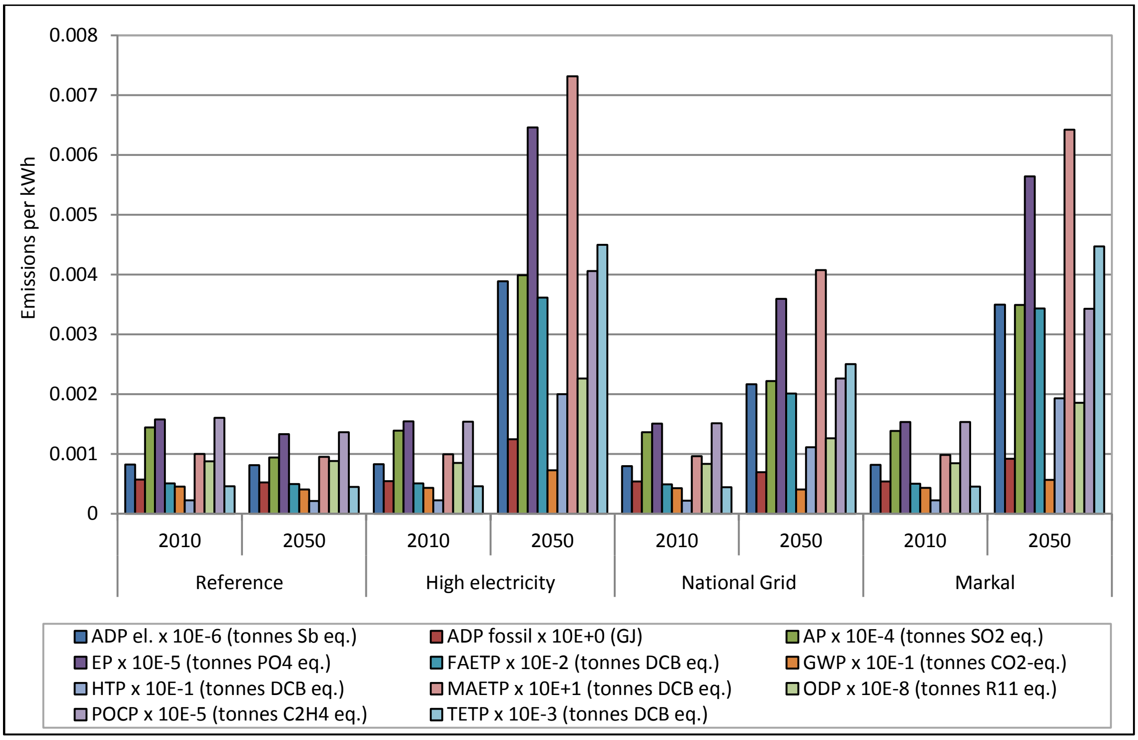


Figure 169 Comparison of environmental impacts per kWh delivered for National scenarios for the year 2010 and 2050.

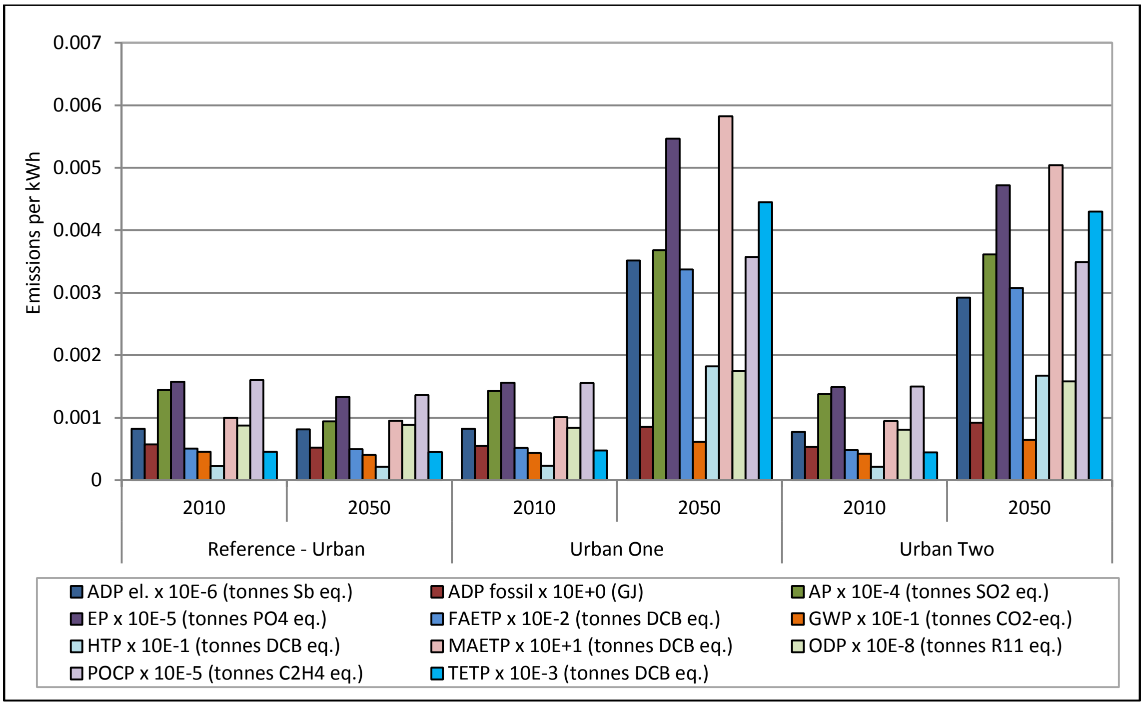


Figure 170 Comparison of environmental impacts per kWh delivered for Urban scenarios for the year 2010 and 2050.

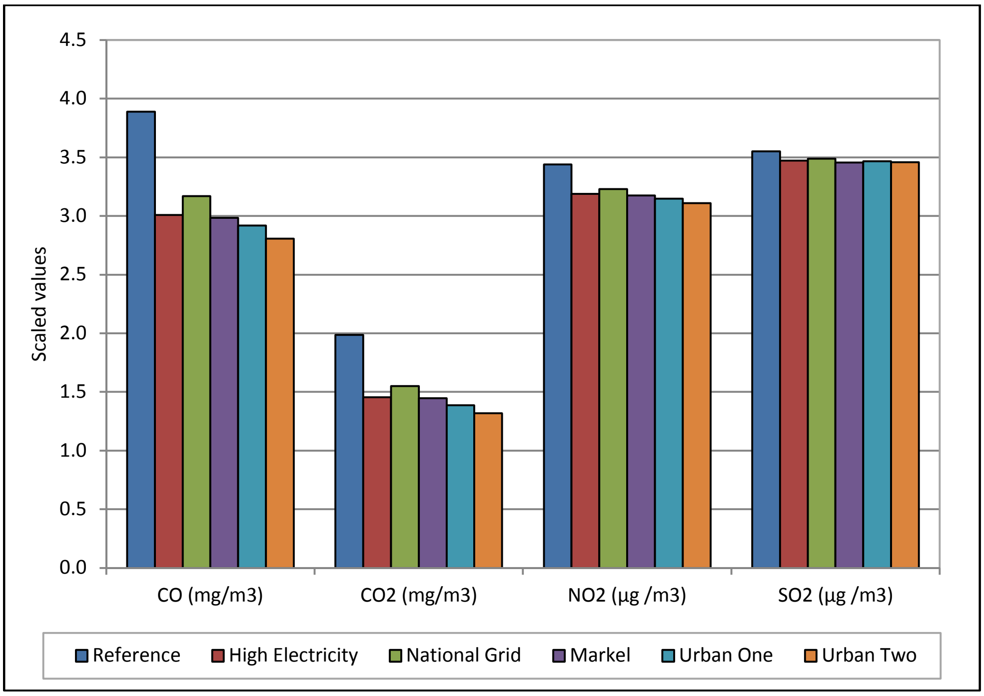


Figure 171 Comparative indoor air quality impacts for all scenarios.

8.3.2 Techno-economic sustainability assessment

This sub-section discusses the results of the economic and technical assessment of national and urban scenarios. Four indicators reflect the costs of each scenario and a further nine technical indicators are shown that are used to assess the broad technical aspects of the studied heat systems and their applications within the scenarios – see Figure 172.

Capital, Operation & maintenance, energy costs and systems costs per kWh - there is a trend towards capital intensive systems within the High electricity, National Grid and Markal scenarios. This reflects increasing sophistication and focus on renewables and community heat provision systems. The High electricity scenario has the largest capital investment requirement with both the National Grid and Markal scenarios experiencing very similar O&M and Energy costs – the cheapest cost overall is the Reference scenario, however this scenario does not meet the carbon targets. The Markal scenario reflects an increasing use of electricity for heating but also an ever growing use of district heating – this can be seen as nearly 60% of the overall costs. In terms of cost per kWh delivered – the Reference scenario is the lowest 7.8 p/kWh and the highest the High electricity 19 p/kWh - this scenario shows a higher cost for space and water heating due to its emphasis on electricity use over the timeframe. The National Grid scenario attends to the carbon target and produces a cost of 13.0 p/kWh over the 40 year period.

The Urban One and Two scenarios show a reduced overall cost as it only covers the requirements of cities: principally the 20 most populated cities in the UK. The proportion of costs associated with heating and electrical requirements is in line with the High Electricity, National Grid and Markal scenarios. The Urban One and Two scenarios have very different costs with the Urban Two overall the most expensive by approximately 40% at £7.2 billion compared to Urban One - £1.4 billion and Reference-urban – the latter is the cheapest £0.6 billion. The Urban Two scenario has the highest capital and O&M costs – this is because of the extensive use of district heating and CHP systems in the scenario. However, the Urban One scenario shows higher energy supply costs mainly through its use of more expensive electricity for the substantial quantity of ASHP and resistance heating systems that the scenario depends on.

System effectiveness and efficiency – this is an indicator of how effective and efficient the heating and cooking scenarios and the systems within them are. The reference scenario has the lowest value indicating the current awareness and familiarity with gas boiler type systems that dominate this scenario. The highest value (lower values preferred) is for High electricity which has a perception of high cost, relative inefficiency and effectiveness especially for space heating.

The Urban One scenario also has a higher value compared to Urban Two; this again is due to the high level of electricity use in the scenario and peoples poor impression of electric heating. The reference-urban scenario has the lowest impact.

Safety, regulations and uses – the Reference scenario exhibits the highest value - the remaining scenarios have very similar values. This combined indicator considers overall safety and the impact of regulations on system types and scenarios. Here, individual gas with extensive pipe arrays are considered a safety risk whereas electricity and centralised heating systems have fewer safety concerns and regulations, and are supportive of new electricity heat such as ASHP.

The urban scenarios reflect a similar pattern to the national level with the Reference-urban offering the largest impacts again due to the extensive use of gas and its pipe network within apartment blocks.

Heat technologies and energy sources – this shows how each of the scenarios is assessed against the opportunity of renewable energy technology and system link-in. The highest value is the Reference scenario having little or no renewable heat technologies or sources of energy derived from such technologies and sources. All other scenarios are better through their positive inclusion of solar thermal, district heating and heat pumps during the scenario period. The best overall performer is the Markal scenario.

The Urban One and Urban Two scenarios have similar values whereas the Reference-Urban exhibits the greatest impacts. The former two scenarios benefit through their greater use of CHP, district heating and solar thermal.

Heat control and management – this indicator is a measure of the extent of heat system impacts related to control and management of heat. The Reference-national scenario has the lowest value suggesting a higher element of householder control and choice as this is based on individual gas boilers. The other scenarios have more control given to others (community, energy service companies etc.) and are therefore regarded less positively.

For the Urban scenarios, a similar picture emerges with the Reference-urban performing best again with gas boilers. The Markal scenario exhibits the highest value through its use of larger centralised and community focussed systems.

Diversity of heat – the diversity of heat is seen as a positive characteristic and one that offers great choice and flexibility to a system. The Reference scenario offers relative limited diversity away from individual gas boilers and electricity derived from natural gas, coal and nuclear. Developing diversity is indicated in the other scenarios (lower values) and where district heating is used extensively as in the Markal scenario this is favoured. Further, the Urban Two scenario provides considerable diversity of heat especially when consideration is given to the range of heat sources available to such systems (gas, biomass, etc.).

Demand implications – with increasing or dramatically changing energy demands there are implications on the energy supply systems especially the electricity and gas networks. Although the majority of scenarios have similar values - the National Grid scenario has the highest and Markal the lowest. National Grid has a slowly declining use of individual natural gas boilers and a similar slow increase in ASHP use; both can provide network demand swings and offer little element of storage.

The Urban Two scenario performs best through its provision of energy storage and flexibility in time/demand usage.

Support to technologies – a measure of the technical and programme support required to technologies and their systems to enable them to function effectively and efficiently. The best performing scenario is the Reference-national. Highest is the High electricity scenario requiring more support to achieve its aims especially relating to insulation levels, storage of energy and the clustering of systems within an energy network.

The Urban Two is the best urban scenario for this indicator; the change to a centralised heat providing system can use several energy types and its provision promotes switching and can move forward with progressions in insulation supporting.

Carbon measures and concerns – carbon concerns are highlighted in the Reference scenario (highest value) reflecting the high carbon electricity mix and the scenario focus on natural gas. In addition, this is also shown in the Reference-urban and Urban One scenarios that exhibit the extensive use of natural gas and the electrification of heat. Urban Two is the preferred scenario with important carbon measures being implemented.

Fuel resilience – the Reference scenario is dependent on imported or restricted fuels reducing its flexibility and assuming a high import dependency represents an undesirable scenario. In contrast, the Markal and Urban Two are the preferred scenarios, although in this form it uses gas for district and CHP heat, it can potentially use other renewable sources, providing substitution routes.

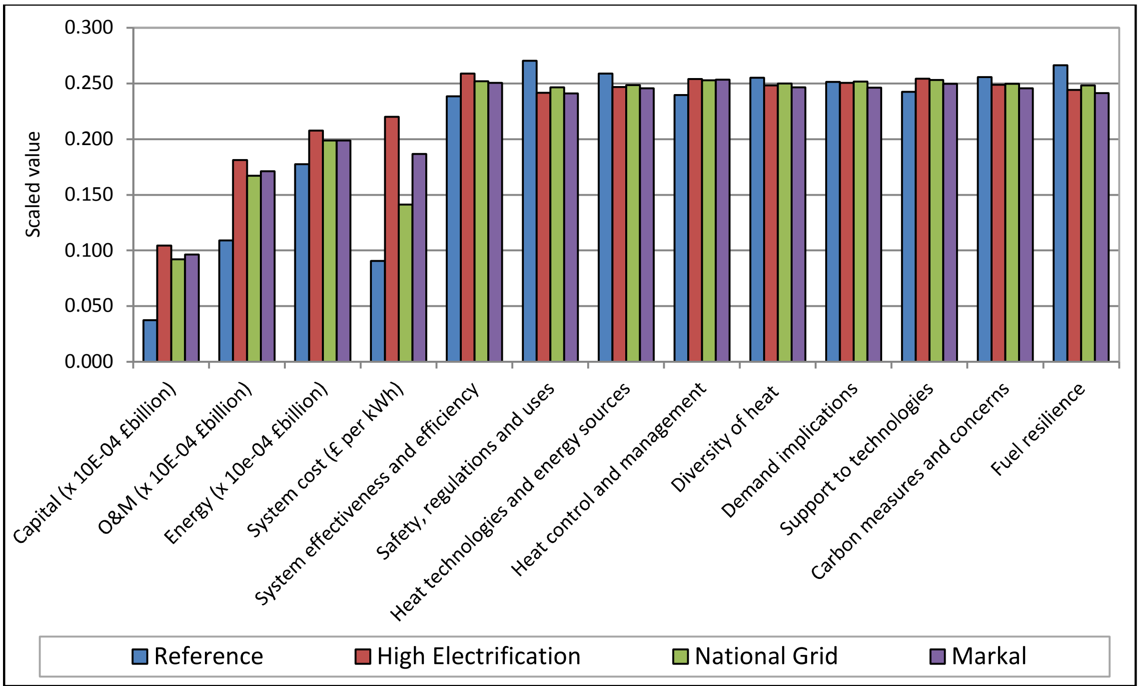


Figure 172 Techno-economic comparisons of UK national heat scenarios.

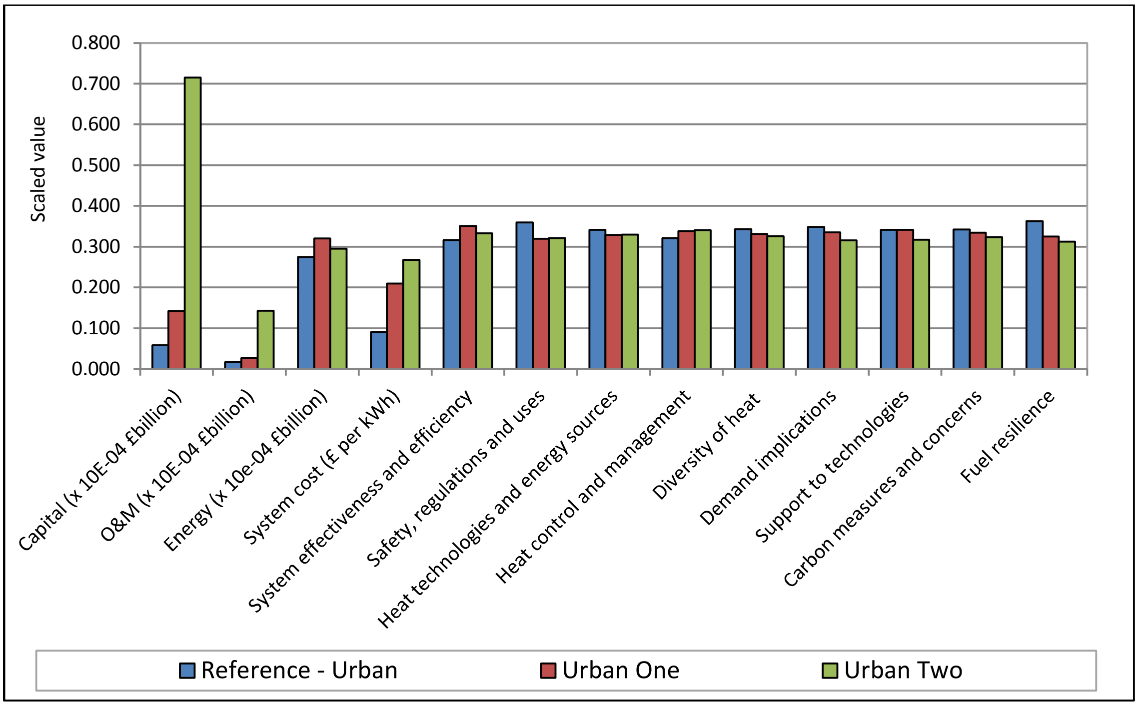


Figure 173 Economic-technical comparisons of urban scenarios.

8.3.3 Social sustainability assessment

This sub-section considers the National and the Urban scenarios based on their social sustainability aspects. Six social indicators as developed and discussed in Chapter 6 and three environmental indicators as described in Chapter 4 are used to compare and contrast the scenarios - this is depicted in Figure 174.

Social timing – expresses the overview of householders opinions related to costing dynamics, system lock in and time related implementation issues. Across the four national scenarios, there is little separation between them – the Markal being of lowest value overall and the Reference-national the highest. Markal performs best due to moderate increase in ASHP over the 40 years and its increasing district heating element and exhibiting new energy routes to markets, greater use of localised approaches to energy and community involvement.

A similar position is reflected at the urban level – the Urban Two scenario performs the best again through its use of community based heat-providing systems.

Development implications – are a measure of stakeholders' views on developmental aspects of urban energy. The Reference scenario has the highest value reflecting the vulnerability of existing systems and their poor developmental prospects. The Markal scenario has the lowest value as the major contributing heat-providing systems offer new routes to markets, localised approaches to energy and are less threatened by regulation changes.

The Urban Two scenario with its focus on district heating and CHP systems is the best performer.

Interaction and ownership – relates to the extent and opportunity of community involvement in domestic heat provision. Although all scenarios are of similar magnitude except for the Reference, the best performing is the Markal. This scenario allows customer interaction and agreement to reduce network impacts through the use generally of community based systems such as the common ASHP, district heating, CHP and solar thermal.

From the Urban scenarios the lowest is the Urban Two scenario providing community involvement through its district heating approaches and emphasis on household information, knowledge and the systems limitations.

System perceptions and experience – expresses the overview of opinions concerning systems performance and intrinsic value. The Reference scenario is favoured with the lowest value and positive perceptions and experience especially relating to the use of individual gas boilers and the associated wet heating systems. The highest (less preferred) scenario is the High electricity – this is through negative perceptions about the possible cost of future electricity, less than effective heating systems and greater pollution through the generation of electricity.

At the Urban level, the Reference-urban is preferred and Urban One – the all-electric scenario less preferred. This relates again to the occupants opinions about the potential high cost of electric based systems.

Acceptability of upstream factors – represents occupants' views on upstream impacts from future electrification of heat. The all-electric based scenarios perform the worst – High electricity and Urban One. The Reference-national and –urban are preferred.

Low income – high cost measures – this is a basic indication of fuel poverty vulnerability. The preferred options are the Markal and Urban Two scenarios typically providing a community approach to heat supply and one in which fuel poverty is better identified and managed. The High electricity and Urban One scenarios exhibit higher values due to higher levels of fuel poverty vulnerability for households through the scenarios prominent heat-providing systems fuelled from electricity.

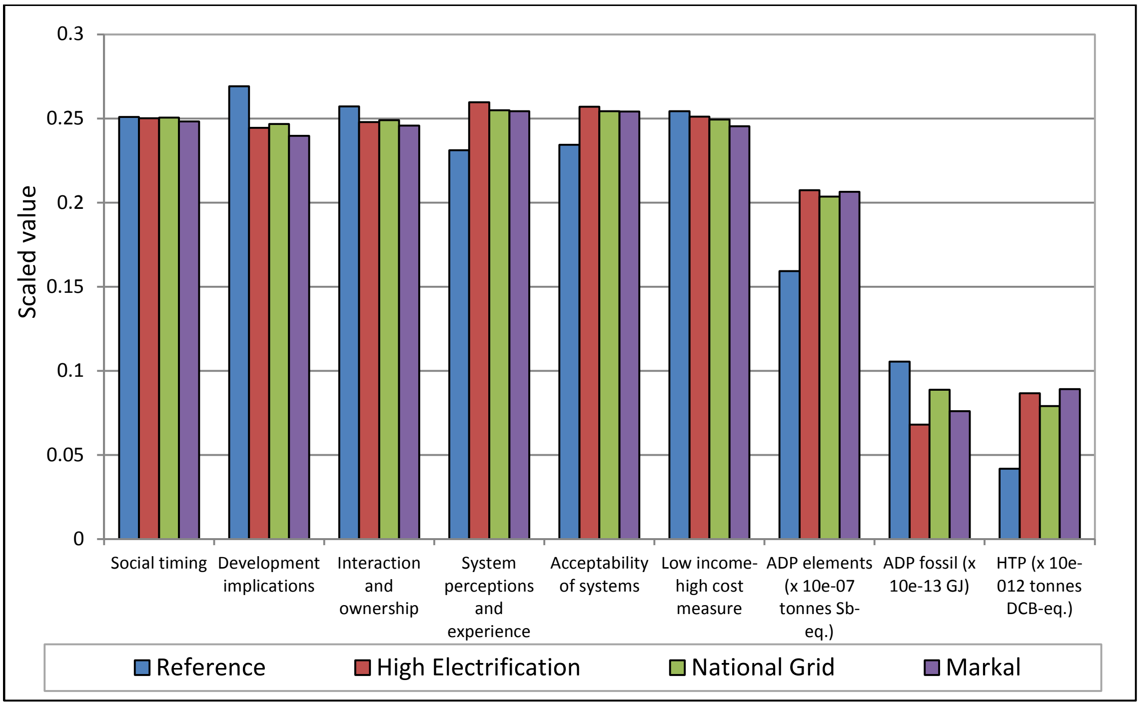


Figure 174 Social comparison of UK national heat scenarios.

[ADP elements, ADP fossil and HTP included as social indicators].

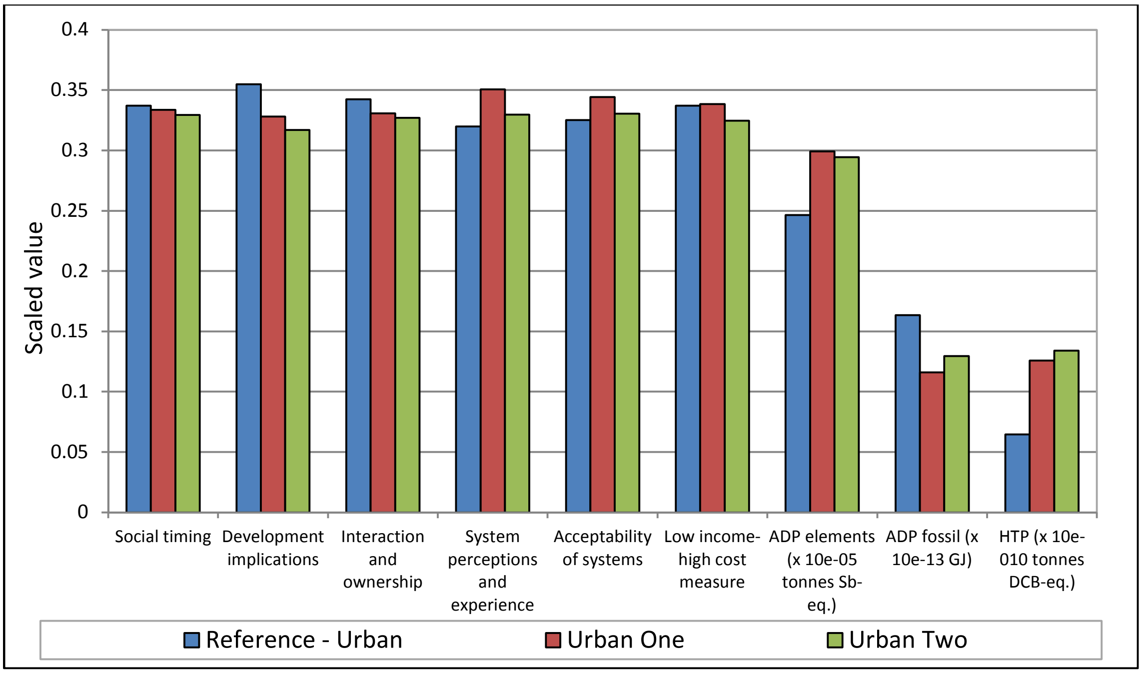


Figure 175 Social comparison of urban heat scenarios

[ADP elements, ADP fossil and HTP included as social indicators].

8.4 Summary of sustainability assessment of future UK energy scenarios

- Using the results presented above, the environmental, techno-economic and social indicators have been aggregated through MCDA assuming equal weights for all the sustainability aspects.
- As shown in Figure 176 and Figure 177, the Markal scenario for the National Scenarios and the Urban Two within the Urban Scenarios appear to be the most sustainable options based on the cumulative impacts across the scenario timeframe.
- The analysis suggests that at National level, the Markal scenario although offering the most sustainable approach over the 40 years is relatively costly and not as environmentally good as the decarbonised High electricity scenario. However, technically and socially the Markal scenario is a better option.
- For the Urban scenarios, Urban Two is the preferred option to Urban One (electrification of heat) for both the techno-economic and social impacts. The Urban One scenario although ranked second, is environmental strong only as long as the electricity mix is decarbonised.

Figure 176 Overall MCDA results for National scenarios including impacts for all years 2010 – 2050.

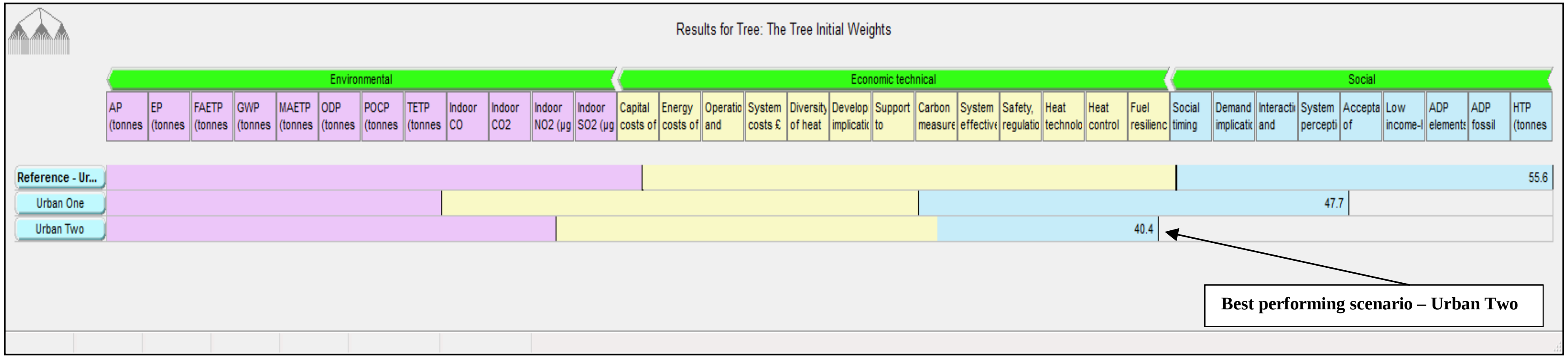


Figure 177 Overall MCDA results for Urban scenarios including impacts for all years 2010 – 2050.

8.5 Summary

This chapter has explored the sustainability of energy scenarios. The assumptions for the various scenarios considered are detailed as follows:

- Reference-national – depicts a future where little is done to decarbonise the electricity supply mix or to reduce overall domestic demand. The principle heating system remains individual gas boilers.
- High electricity – this scenario focuses on the decarbonisation of the electricity supply while increasing domestic electricity demand through the promotion and use of heat pumps and new resistance type heating.
- National Grid – considers an approach where a moderate change is made away from gas for heating to one of heat electrification through heat pumps.
- Markal – indicates a future where heat is provided to households through heat pumps but more importantly, the use of district heating systems.
- Reference-urban – follows the same profile as for the Reference-national but is urban based.
- Urban One – an urban based scenario where the principle means of heating is through the use of heat pumps and resistance type heating. Individual gas boilers are phased out and the electricity supply mix is substantially decarbonised.
- Urban Two – describes an urban approach to energy supply and use through the extensive use of district heating, common hot water systems and some heat pumps.

The outcomes of the scenarios are as follows:

- From the environmental point of view, over the 40 year scenario period, the High electricity scenario is the best option providing the lowest GWP, ODP and POCP emissions. The Markal scenario is a close second and the Reference scenario the worst performing.
- All national scenarios show environmental impact increases over 2010 levels except for GWP where the High electricity, National Grid and Markal show decreases of 35% overall.

- For the urban situation, the Urban One scenario is ranked as top from the environmental aspects of the study. The Urban One and Two show decreases for AP, GWP, ODP and POCP between 2010 and 2050.
- Overall costs are higher in all scenarios compared with 2010. The Reference and Urban One scenarios are the least cost options and the High electricity the most costly. Reductions in cost per unit would be expected as technologies become more widespread especially ASHP although the cost of excavation and reinstatement required for district heating is not expected to reduce.
- From the technical point of view the Markal and Urban Two scenarios perform the best. Both can make use of changing and improving energy sources and provide a capacity for heat storage and management of energy flows especially concerning reduction of peak demand.
- In a similar manner to the technical, the Markal and Urban Two scenarios perform best in the social category, each possibly providing greater community involvement and control over energy provision, securing better energy deals through cooperation and valuing robustness and the long term view.
- Indoor air quality is dependent on many components – in the scenarios air quality is considered with respect to gas or electric cooking and boilers. The Markal and Urban Two scenario perform the best with less emphasis on individual boilers or gas cooking.
- Overall, through the MCDA modelling results, the Markal Scenario and the Urban Two scenario are ranked the best for the national and urban settings respectively. The Markal and Urban Two scenarios exhibit strong economic and social aspects and are close contenders to the High electricity and Urban One scenarios from the environmental aspects.

The final Chapter outlines the conclusions, recommendations and future work from this research.

9. Conclusions, recommendations & further work

This research has assessed the sustainability of the electrification of heat, taking into account environmental (Chapter 4), techno-economic (Chapter 5) and social aspects (Chapter 6) and considering both current situation and possible future scenarios. The study has been applied, in the UK context, to a series of heat-providing systems typically found in city residential apartment blocks. Eight systems have been assessed: all-electric, gas only, combined and centralised community heat systems. The most sustainable heat-providing systems have been identified using multi-criteria decision analysis (Chapter 7) based on different preferences. The assessment of future scenarios (Chapter 8) involved the consideration of four potential electricity mixes from 2010 to 2050 and comparing to the present day. The scenarios considered four different approaches to residential heat supply at the national level and three specific to cities.

9.1 Conclusions

The conclusions resulting from this research address the aims and the objectives as detailed in Chapter 1 and described as follows:

1. Compare and contrast the environmental, techno-economic and social sustainability of gas and electricity supply to city households in the UK in order to identify impacts of the electrification of heat and compare current energy supply and usage with options - derived from scenarios - that will be appropriate up to 2050;
2. Develop an integrated sustainability assessment framework and indicators applicable to the electrification of heat, taking a life cycle approach; and
3. Conduct life cycle assessment using a range of tools and approaches including - life cycle assessment (LCA), air quality monitoring (AQM), life cycle costing (LCC), social surveys (SS), multi-criteria decision analysis (MCDA) and scenario analysis (SA).

The overall conclusions are summarised in Section 9.1.1 – 9.1.3, and recommendations in Section 9.2. Finally, suggested areas for future work are given in Section 9.3.

9.1.1 Current electrification of heat of residential heat supply in cities

This section refers to the sustainability assessment of current heat-providing systems and heat electrification in cities. The main conclusions from the environmental, techno-economic and social assessment are as follows:

Life cycle environmental impacts

1. Natural gas based systems are the best environmental options of the systems considered, based on the 11 environmental indicators estimated in this work. The lowest impacts are found for the individual gas boiler system (for nine indicators) followed by the combined solar thermal and gas system. The latter performs best for the depletion of fossil resources and global warming potential because of its supply of renewable energy via the solar thermal panels.
2. The electric panel, electric storage and ASHP have the highest environmental impacts which are on average 2.5 times higher than for the gas based systems (gas boiler, solar thermal and gas, district heating and CHP) respectively. The combined gas and electric system also performs poorly and is ranked 3^{rd} after the electric storage system.
3. The global warming potential is the highest for the electric panel, electric storage and ASHP with 11,500; 12,000; and 8,900 tonnes CO_2 eq. over 40 years, respectively. By comparison, the gas based systems - gas boiler, district heating, community CHP and solar thermal and gas - have the GWP of 4,300; 4,600; 4,300; and 4,150 tonnes CO_2 eq. respectively. For the hybrid combined gas and electric system, this impact is estimated at 8,600 tonnes CO_2 eq. over 40 years.
4. For all eight heat-providing systems, the life cycle stage with the highest contribution to the environmental impacts is the use of electricity and natural gas in the operation stage. The largest contributions from these stages are in the all-electric systems across the 11 indicators: panel system (65% to 99%), storage system (70% to 99.0%), and ASHP system (47% to 98%).
5. The contribution of the components of the heat-providing systems is relatively small. For example, the GWP associated with the components is highest for the district, ASHP, community CHP and solar thermal and gas system at 140, 175, 225 and 227 tonnes CO_2 eq. per system, respectively. The remaining all-electric

systems, gas and combined have a lower GWP at electric panel 125, electric storage 123, gas boiler 122, and combined system 108 tonnes CO_2 eq. per system, respectively. The GHG emissions arise from the life cycles of ferrous and non-ferrous metals during component and system manufacture.

6. The majority of metals used in the systems are both recyclable and in-demand - this plays a role in reducing the environmental burdens through system crediting and further reductions can be made as industrial recycling rates improve.
7. Installation impacts across all systems are relatively minor compared to overall environmental impacts ranging from 0.08% for the electric panel to 2.07% of overall for the district heating system across all impact indicators.
8. The impacts from maintenance are approximately four times higher for ADP fossil, EP, GWP, ODP and POCP for the gas related systems than for the electric based systems owing to strict requirements for the safe installation of gas supplies, use of natural gas fuelled equipment and household wet system maintenance.
9. The impact of increasing hot water use against space heating shows environmental increases for the gas boiler and ASHP systems and decreases for the combined gas and electric system, solar thermal gas and community CHP systems. This reflects the advantages and increased efficiencies of the more centralised heat supplies to apartment blocks.

Direct indoor environmental impacts

10. Indoor air quality monitoring shows increased emission levels during cooking events in households using gas and electric hobs. However, gas fuelled homes produce substantially higher levels of peak CO emissions (on average 5 times more) than all-electric homes during cooking events.
11. Emissions of CO_2 during cooking events are 3-5 times higher in homes using gas cooking than those using electricity both at mean and peak levels. All-gas homes come close to or exceed established NO_2 and SO_2 limits. The 24-hour test reveals substantially (ten times) higher concentrations of SO_2 in gas fuelled homes.
12. During winter, overall emission levels in the kitchen are elevated compared to summer - this is reflected at both peak and mean levels and is due to lower house ventilation rates in the winter.

Life cycle costs

13. Individual gas boiler system for cooking, space and water heating is the least costly at £2,510,400 over 40 years of which £984,022 is due to the cost of the gas.
14. The electric panel is the most costly all-electric system at £3,001,811 due predominately to the costs of (standard rate) electricity for all heat demand. Gas prices would need to increase 30% every five years for all-electric systems to closely match the energy costs of the gas boiler system over the 40 year period. For the ASHP system (the most efficient all-electric system) to become comparable to the life cycle costs of the gas boiler, the cost of gas would need to increase to above 6.5 p/kWh, (from current 4.0 p/kWh) with electric prices remaining as in the base case.
15. The life cycle costs over the 40 year period are similar for the gas boiler £2,500,500, combined gas and electric £2,700,000, electric storage heater £2,800,000, and ASHP £3,000,000. This is essentially because of the consumption of cheaper gas for the first two systems and the use of off-peak and commercial rate electricity for the latter systems, respectively.
16. The CHP and district heating systems are the most costly overall £3,700,000 and £3,600,500 respectively owing to the high initial construction costs and the level of on-going system repair and maintenance. The gas boiler system also has considerable life cycle maintenance and servicing costs, contributing 25% to the overall life cycle costs.
17. Equipment and components that have the highest contribution to the life cycle costs of systems include the energy convertors such as gas boilers 8%, storage heaters 8%, solar thermal panels 7.2%, ASHP units 7.1%, and electric panels 7%.
18. Initial construction costs (as incurred by the developer) are lowest for electric systems and highest for the community CHP and district heating systems, whereas, operational energy costs (as incurred by the user) are lowest for the CHP system.

Social aspects and perspectives

19. Although effective in use, seen as low indoor polluters and safer overall, apartment occupants view electric systems as expensive to operate. There is an appreciation of gas space heating especially amongst those who have experienced this type of system.
20. Occupants using alternative heat providing systems such as the combined gas and electricity system view them positively in terms of their efficiency but are wary of any third party involvement particularly regarding pricing, lack of supplier choice, and overall transparency.
21. Householders recognize that a switch from gas to the greater use of electricity for heating has occurred in cities and that this has happened in newer or retrofit buildings constructed generally with a smaller number of bedrooms.
22. Organisations consider the electrification of heat to date as a short term event or trend in cities where developers and others have taken advantage of a transient regulatory structure and flexible cheaper implementation. The construction of smaller well insulated city homes has supported the use of electricity for heat requiring lower heat demand and less extensive systems. However, a second wave of heat electrification is on the horizon particularly through the proposed use of heat pumps.
23. A similar trend is observed by organisations – but this is a change from individual gas to centralised forms of gas sourced heat supply to apartments including district and CHP heat-providing systems.
24. Any further substantial move from gas to electricity for heat would require a monumental change involving considerable additional investment and reconstruction along with new approaches of working and interacting with supply networks and customers.
25. Peak electrical demand and the clustering of the same energy technologies is a particular problem for supply and can make the further growth in the use of electricity difficult unless time-control and localised energy storage are implemented.
26. Renewables may assist in provisioning low carbon electricity; nevertheless, realistic timeframes for their implementation and time responsibilities are paramount to continue the synchronisation of city supply systems.

Multi-criteria decision analysis

27. Assuming equal importance of all sustainability aspects considered and applying MCDA indicates that the district heating represents the best heat-providing system studied here. For example, the district heating system comprising of a centralised energy plant, hot water distribution system and household heat stations has comparable environmental emissions to the individual gas boiler while benefiting from reduced indoor direct emissions through electric cooking.
28. The all-electric based systems perform poorly particularly across the environmental and social indicators reflecting environmental concerns of electricity generation and householders' negative perceptions of electricity use for heat. Using a decarbonised electricity mix (as proposed in 2050) improves the all-electric systems overall performance but does not change the ranking of the studied heat-providing systems.

9.1.2 Future electrification of heat of residential heat supply in cities

This section refers to the sustainability assessment of future heat-providing systems and heat electrification in cities through scenario analysis.

Scenarios

1. The most sustainable scenarios are the Markal at the national level and the Urban Two scenario at the urban level.
2. In the Markal scenario there is a substantial decrease in demand for space and water heating while cooking becomes entirely electric by 2050. An increased use of nuclear power in the electricity generation mix is assumed and the substantial use of CCS for both coal 20.3% and gas 10.4% by the end of the period. Markal is typified by the increasing installation and use of air source heat pumps 75% and district heating 10% systems over the 40 years. Individual gas boilers are removed by 2050. The Markal scenario is the best option overall of the national scenarios and specifically for the techno-economic and social impacts.
3. In the Urban Two scenario residential heat supply is through district heating 33%, CHP 20%, ASHP 20%, combined gas and electric systems 10% and other electric and solar thermal 17% by 2050. There is a decrease in demand during

the 40 year period. The electricity generation mix follows that for the Markal scenario. The Urban Two is the best urban option overall for the environmental, techno-economic and social impacts.

The main conclusions from the scenario environmental, techno-economic and social assessment are as follows:

Life cycle and direct environmental impacts

1. The Markal scenario is the best performer environmentally on the national scale but has the highest overall scenario impacts in the FAETP and MAETP indicators due to the use of district heating systems and the greater use of coal CCS in the generation mix respectively. Markal has low indoor impacts through the growing use of electric cooking associated with district heating and ASHP systems.
2. For all national scenarios eight environmental impacts increase between 2010 and 2050 - ADP elements, AP, EP, FAETP, HTP, MAETP, ODP, POCP. The global warming potential decreases for the High electricity, National Grid and Markal scenarios due to the decarbonisation of electricity.
3. The Urban Two scenario is the second best urban related performer environmentally with the highest impacts in the AP, EP, MAETP and TETP indicators. The higher levels are due to the growing use of electricity for heat and particularly the use of coal CCS. Urban Two also has low indoor impacts through the use of electric only cooking.
4. The urban scenarios all show increasing impacts across indicators – EP, FAETP, MAETP, POCP and TETP when comparing 2010 to 2050. Reductions in emissions are shown by Urban One and Two in GWP and ODP through the decarbonisation of electricity and the decreasing use of individual gas boilers respectively.
5. Decreasing demand and increasing household numbers produce increases in impacts for all national and urban scenarios except for the Reference where demand increases between 2010 and 2050. Markal grows from 430 g to 565 g CO_2 eq. per kWh, Urban Two 425 g to 645 g CO_2 eq. per kWh whereas the Reference declines from 456 g to 405 g CO_2 eq. per kWh.

6. Life cycle assessment shows that 94 Mt of CO_2 eq. could be generated over 40 years by using electric-only systems for residential heat supply in cities in England (using 2010 as the base year) assuming no decarbonisation. If the decarbonisation of electricity took place to government planned levels of 80% at the base year, life cycle impacts could be reduced to 10 Mt CO_2 eq. over 40 years.

Life cycle costs

7. The Markal scenario is the best national performer from the techno-economic aspects. Although having a high overall capital and operation and maintenance cost, Markal makes use of changing and improving energy sources and provides a capacity for heat storage and management of energy flows especially concerning reduction of peak demand.
8. The Urban Two scenario is the best option at the urban level. Urban Two is costly both in terms of capital and O&M but is strong in the other techno-economic indicators. Urban Two offers considerable diversity of heat when considering the range of heat sources available and the extensive use of district heating and CHP in the scenario.

Social aspects and perspectives

9. The national scenario Markal is the best option from the social sustainability perspective. Markal has the increasing use of ASHP and to a lesser extent district heating – this is reflected in the higher impacts for the ADP element and HTP. Drawing on the increasing use of air source heat pumps and a decarbonised electricity supply – this scenario benefits from development implications including supportive regulation changes and localised approaches to energy.
10. The Urban Two scenario performs best at the urban level from the social sustainability point of view. Although offering higher ADP element and HTP impacts through the use of ASHP and wet heating systems – Urban Two has strengths in interaction and ownership, social timing and response to fuel cost vulnerability.

9.2 Recommendations

The following recommendations are aimed at improving and accommodating the electrification of heat in residential heat supply in cities:

9.2.1 General recommendations

1. Identifying sustainable heat-providing systems should be carried out on a life cycle basis and considering a range of environmental, technical, economic and social aspects rather than focusing solely on (direct) carbon emissions and costs.
2. Current policy mechanisms do not address the value of future avoided electricity or energy demand – a refocus to incorporate this could change the dynamics of heat-providing system selection and installation. Home and energy efficiency should work hand in hand with electricity or heat generation.
3. The majority of ‘low carbon’ developments to date have been planned and implemented in the public sector. Currently, insufficient ‘carrots and sticks’ are available to try and motivate private developers and ultimately occupants to take up such low carbon measures.
4. Upstream electricity generation is not the only solution to the electrification of heat – an infrastructure development strategy, and intelligent electric management systems at the household level are important to support such a major energy shift.
5. Network operators and suppliers can help change occupants behaviour through pricing signals or even the implementation of credits that can be made for not using energy at a particular time – this approach should be considered further.
6. The construction industry itself is relatively conservative in nature. Developers and builders want to be able to “build and leave” and perceive that low carbon technologies will create both installation and maintenance problems. Methods to consolidate longer term views and approaches are required.

9.2.2 Specific recommendations

1. The most sustainable heat-providing system according to the study is the district heating system. The system performs best overall from the environmental,

techno-economic and social aspects. The combined heat and power system (CHP) and the combined solar thermal and gas systems are close contenders. For apartment blocks, the district and CHP heat-providing system are recommended. The solar thermal and gas system although providing renewable heat is constrained by the strict gas supply construction and maintenance requirements for apartment blocks.

2. Of the all-electric systems studied – the communal air source heat pump (ASHP) system is recommended where apartment blocks are constructed with smaller well insulated apartments and the electricity is decarbonised.
3. Scenario analysis shows that a balanced portfolio of heat-providing systems consisting of district heating 33%, CHP 20%, ASHP 20%, combined gas and electric systems 10% and other electric and solar thermal 17% by 2050 provides the most sustainable heat supply for cities. Electricity would be decarbonised by 80% by 2050 in line with the UK's broad carbon reduction target.
4. The 'electrification of heat' as part of the broader heat supply provision to city households is shown to be feasible and sustainable given the decarbonising of electricity. The complete electrification of heat is not recommended due to environmental, techno-economic and social impacts described previously.

9.3 Future work

The following areas of research are recommended for future work:

1. Further analysis of alternative heat providing systems that may be influential in the future including heat from biomass boilers and non-conventional fossil fuels such as shale gas.
2. Consideration of locally-generated electricity into heat-providing systems, particularly photovoltaic systems and wind turbines.
3. Research into the life cycle sustainability of urban energy storage systems particularly at the centralised and household levels.
4. Further research and analysis into the impacts and costs of city energy infrastructure development to accommodate changes in energy demand.
5. Potential extension of the work to include a larger number of all-electric and all-gas homes for indoor air quality monitoring to complement the current IAQ work.

6. Data collection of actual extractor fan operation, door and window opening and number of persons present indoors to supplement the air monitoring data.
7. Research further into the cost of maintenance specific to gas and electricity networks supplying heat-providing systems ensuring all relevant cost and impacts are considered equally.
8. Further develop the questionnaire survey approach to improve inclusivity, especially amongst those who do not normally have access to or use the internet.

9.4 Concluding remark

This work has integrated environmental, techno-economic and social assessment tools and indicators into a framework for assessing the sustainability of the electrification of residential heat in cities. This research demonstrates the advantages and disadvantages of using electricity rather than gas for heat both in the present and the future. The findings suggest that the electrification of heat in cities could be sustainable. However, the choice of the most sustainable heat-providing options in the future, including that of the ‘electrification of heat’, will depend on the extent of the decarbonisation of the UK electricity supply as well as the relative importance placed on sustainability impacts by different stakeholders. It is hoped that this work provides a foundation for a better understanding of sustainability issues associated with the heat electrification and that its findings will inform policy, contributing towards more sustainable development of the sector.

Postscriptum

As is evident from UK government policy, increasing awareness and research initiatives - heat supply in cities and particularly the electrification of heat is of growing interest. Greater attention is now given to the future prospects and concerns relating to changes and long term sustainability implications of residential heat supply. However, there is no resource out there that helps understand and comprehend the integrated complexities of heat supply in cities. This research addresses this issue by providing a comprehensive framework that can manage complexity, assist analysis and decision making from the environmental, techno-economic and social points of view.

In the wider world context, the field of electrification of heat clearly faces a number of challenges related to the complexity and uncertainty of heat energy supply and demand within countries and regions under consideration. Existing heating and supply networks reflect the choices made in the past by countries in Europe and the rest of the world, for example, the UK’s decision to access North Sea natural gas for central heating or Denmark in developing extensive district heating networks (Möller and Lund, 2010; Toke and Fragaki, 2008; Torekov, 2007). Currently the electrification of heat is most evident in countries where the national carbon intensity of electricity is considered low - particularly Sweden and France. Countries with substantial nuclear capacity including Finland and several East European Countries also use electricity extensively for heat and where hydro-electricity is readily available such as Norway (Thyholt and Hestnes, 2008) and several provinces in Canada significant heat electrification has also taken place (NRC, 2003). An indicator of the electrification of heat in domestic properties is the growing trend of heat pump installation this is particularly high in Sweden, Switzerland and parts of Austria where they are considered as an environmental beneficial solution. Further afield and exhibiting quite different situations, China, Japan and New Zealand are also experiencing the electrification of heat.

The uptake of renewable forms of generation, increasing electricity generating efficiency and current European policy is encouraging the electrification of heat particularly the wider uptake of heat pumps. Although the benefits vary, cities, regions, and countries now have to make decisions on how best to develop their energy actions considering energy security, climate change and other important factors that include social sustainability. This is forcing a cut across traditionally independent but now increasingly inter-related sectors such as electricity, heating and transport but also through the increasing importance of sustainable energy across borders and through common transmission systems. With recent planned and proposed developments in the configuration of installed electricity generating capacity and heat production technologies, the validity of views and rational choices for sustainable heat supply in different parts of the world are becoming more complex and require multi-dimensional inputs and approaches. Such efforts include: innovative regulatory arrangements providing incentives to invest, new business models and relationships, and context specific user-technology advances and improvements.

Therefore, this research has uniquely provided a sustainability framework where the intricacies of each situation can be considered and any decision making process enhanced. The impact of this work is to enable stakeholders to take a whole system approach to sustainable heat supply and assessment within their specific context through modelling the impacts of different criteria. It is anticipated that this research will make a meaningful contribution to energy policy and energy actions in the UK and abroad.

10. References

ABDULLAHI, K. L., DELGADO-SABORIT, J. M. & HARRISON, R. M. 2013. Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking: A review. *Atmospheric Environment,* 71**,** 260-294.

ALLEN, G. 2003. A critique of using grounded theory as a research method. Portsmouth, UK: Portsmouth University, UK.

ALLEN, S. R., HAMMOND, G. P., HARAJLI, H. A., MCMANUS, M. C. & WINNETT, A. B. 2009. Integrated appraisal of a Solar Hot Water system. *Energy,* 35**,** 1351-1362.

AMA 2009a. Domestic Heating Market UK 2009-2013. *AMA Research.*

AMA 2009b. UK Flats Market Completions 2006-2014 London: AMA Research.

APPLEYARD, D. 2009. Renewable Heating and Cooling in the UK. *Renewable Energy World*.

ARASHIDANI, K., YOSHIKAWA, M., KAWAMOTO, T., MATSUNO, K., KAYAMA, F. & KODAMA, Y. 1996. Indoor pollution from heating. *Industrial Health,* 34**,** 205-215.

ARDENTE, F., BECCALI, G., CELLURA, M. & LO BRANO, V. 2005. Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances. *Renewable Energy,* 30**,** 109-130.

ASHMORE, M. R. & DIMITROULOPOULOU, C. 2009. Personal exposure of children to air pollution. *Atmospheric Environment,* 43**,** 128-141.

ASHRAE 2010. Ventilation for acceptable indoor air quality. *Standard 62.1-2010.* USA: ASHRAE.

ASIF, M. & MUNEER, T. 2007. Energy supply, its demand and security issues for developed and emerging economies. *Renewable and Sustainable Energy Reviews,* 11**,** 1388-1413.

ASSEFA, G. & FROSTELL, B. 2007. Social sustainability and social acceptance in technology assessment: A case study of energy technologies. *Technology in Society,* 29**,** 63-78.

BATTISTI, R. & CORRADO, A. 2005. Environmental assessment of solar thermal collectors with integrated water storage. *Journal of Cleaner Production,* 13**,** 1295-1300.

BBC. 2009. *Economy 7 meters in a muddle* [Online]. Available: http://www.bbc.co.uk/blogs/watchdog/2009/01/economy_7_meters_in_a_muddle.html [Accessed October 18th 2010].

BCC. 2005. *Birmingham sustainable energy action plan* [Online]. Birmingham City Council. Available: http://helpdesk.eumayors.eu/docs/seap/330_507_1304007118.pdf.

BEG 2006. Decentralised generation - Independent analysis of the potential role of small scale distributed generation. London: British Energy Group PLC.

BELESSIOTIS, V., MATHIOULAKIS, E. & PAPANICOLAOU, E. 2009. Theoretical formulation and experimental validation of the input-output modelling approach for large solar thermal systems. *Solar Energy,* 84**,** 245-255.

BELLINGHAM, R. 2010. Sustainable Glasgow Report 2010. Sustainable Glasgow.

BERGERSON, J. & LAVE, L. 2002. A Life Cycle Analysis of Electricity Generation Technologies: Health and Environmental Implications of Alternative Fuels and Technologies. Carnegie Mellon Electricity Industry Center.

BERR 2007a. Estimates of heat use in the UK. *In:* BUSINESS, E. A. R. R. (ed.).

BERR 2007b. Meeting the Energy Challenge.

BERTSCH, S. S. & GROLL, E. A. 2008. Two-stage air-source heat pump for residential heating and cooling applications in northern U.S. climates. *International Journal of Refrigeration,* 31**,** 1282-1292.

BIOREGIONAL 2012. Retrofitting district heating systems - creating replicable retrofit models in Hackbridge. BioRegional

BLOM, I., ITARD, L. & MEIJER, A. 2010. LCA-based environmental assessment of the use and maintenance of heating and ventilation systems in Dutch dwellings. *Building and Environment,* 45**,** 2362-2372.

BMRA. 2011. *About metal recycling* [Online]. Huntington: British Metal Recycling Association. Available: http://www.recyclemetals.org/about_metal_recycling [Accessed 28th September 2011].

BOARDMAN, B. 2008. Witness statement of Brenda Boardman. *In:* COURT, I. T. H. C. O. J. Q. B. D. A. (ed.). London.

BOARDMAN, B. 2012. Fuel poverty synthesis: Lessons learnt, actions needed. *Energy Policy***,** 143-148.

BOC 2011. Certified reference material - certificate of calibration. Grimsby, UK: BOC Limited.

BODANSKY, D. 1984. Electricity and natural gas use for residential space heating: U.S. experience, 1976-1980. *Energy,* 9**,** 303-313.

BODIAN, C., ANDREWS, H. & GOLDSTEIN, I. F. 1989. VARIABILITY IN NITROGEN DIOXIDE READINGS WITHIN AND BETWEEN NEW YORK INNER-CITY APARTMENTS. *Environment International,* Vol 15**,** 483 - 488.

BOWITZ, E. & DANG TRONG, M. 2001. The social cost of district heating in a sparsely populated country. *Energy Policy,* 29**,** 1163-1173.

BRADWELL, A. 2010. *RE: Dimplex electric heating solutions interview*.

BRE 2003. Domestic heating by electricity - Good practice guide 345. *Energy saving trust - energy efficiency best practice in housing*.

BRE 2004. Comparison of running costs for different heating options in hard to treat flats. London: Building Research Establishment for Energy Saving Trust.

BRE 2005a. The Government’s Standard Assessment Procedure for Energy Rating of Dwellings 2005 edition, revision 3.

BRE 2005b. Green Guide to Specification BRE Materials Industry Briefing Note 3a: Characterisation. London: Building research Establishment.

BRE 2005c. *Ventilation, air tightness and indoor air quality in new homes,* Berkshire, IHS BRE Press.

BRE 2009a. The Government's standard assessment procedure for energy rating of dwellings - 2005 edition - revision 3. London: published on behalf of DECC by: BRE.

BRE 2009b. Viridian Solar – Clearline Solar Thermal Test Report - Average Household Simulation. London: Viridian Solar for Building Research Establishment.

BRINKLEY, M. 2010. Part L and the fuel factors.

BROMLEY, R. D. F., TALLON, A. R. & ROBERTS, A. J. 2007. New populations in the British city centre: Evidence of social change from the census and household surveys. *Geoforum,* 38**,** 138-154.

BROOKE, S. 2010. Telecon with Simon Brooke - Electricity North West Manchester

BROWN, S. K., SIM, M. R., ABRAMSON, M. J. & GRAY, C. N. 1994. Concentrations of Volatile Organic Compounds in Indoor Air - A Review. *Indoor Air***,** 123-134.

BSRIA 2011. Rules of Thumb - Guidelines for building services (5th Edition) (BG 9/2011) London.

BUILDING, T. G. 2005. *The Green Building, Manchester, UK* [Online]. Manchester. Available: http://www.designbuild-network.com/projects/green-building/ [Accessed June 4th 2010 2010].

BWEA 2010. Embrace the Revolution: Delivering 2020 Manifesto for wind, wave and tidal power. British Wind Energy Association.

CALDECOTT, D. H. J. W. B. 2009. Delivering a 21st Century infrastructure for Britain.

CALG 2000a. Our Towns and Cities: The Future - Delivering an Urban Renaissance. *The Stationery Office*.

CALG 2007a. Building a Greener Future: Policy Statement.

CALG 2007b. Building regulations - Energy efficiency requirements for new dwellings. *In:* GOVERNMENT, C. A. L. (ed.).

CALG 2007c. English House Condition Survey 2007 Annual Report. *Communities and local government*.

CALG 2007d. Homes for the future: more affordable, more sustainable. *Presented to Parliament by The Secretary of State for Communities and Local Government by Command of Her Majesty*.

CALG 2007e. Sustainable Communities Act 2007 - Inspiring the Big Society: a consultation on regulations under the Sustainable Communities Act. London: Communities and Local Government.

CALG 2008a. Domestic heating compliance guide. *Communities and local government*.

CALG 2008b. English house condition survey 2006 - Annual report. London: Communities and Local Government.

CALG 2009. Sustainable New Homes - The Road to Zero Carbon. *In:* GOVERNMENT, C. A. L. (ed.).

CALG 2011. English Housing Survey - Housing Stock Report 2009. London: Communities and Local Government

CARBONTRUST 2008. Solar thermal technology - A guide to equipment eligible for Enhanced Capital Allowances.

CARBONTRUST 2010. Introducing combined heat and power. London: Carbon Trust.

CARRERA, D. G. & MACK, A. 2010. Sustainability assessment of energy technologies via social indicators: Results of a survey among European energy experts. *Energy Policy,* 38**,** 1030-1039.

CARRIER. 2010. *Heat pumps* [Online]. Available: http://www.residential.carrier.com/products/acheatpumps/heatpumps/index.shtml [Accessed November 3rd 2010].

CAT 2010. Zero Carbon Britain 2030 - A new energy strategy. Centre of Alternative Technology.

CCC 2008. Building a low-carbon economy – the UK's contribution to tackling climate change. London Committee on Climate Change.

CERT 2009. Carbon emissions reduction target amendments - summary of consultation responses and government response. *In:* DECC (ed.).

CHARON, J. M. 1995. *Symbolic interactionism,* London, Prentice-Hall.

CHURCHER, D. 2008. Whole-Life Costing Analysis. Bracknell: BSRIA.

CIBSE 2008. *CIBSE Guide M: Maintenance Engineering and Management,* London.

CIBSE 2010a. *Domestic heating design guide*.
CIBSE 2010b. Indicative life expectancy for building services plant, equipment and systems. London: CIBSE.
CIBSE. 2010c. *Solar thermal – solar hot water heating* [Online]. London: The CIBSE Journal CPD Programme.
CITIES, E. 2005. A collection of case studies demonstrating exemplar 'sustainable community' projects across Europe.
CLASP 2012. Liverpool City Region Sustainable Energy Action Plan. Liverpool.
CML. 2001. *CML 2 baseline 2001* [Online]. Centre of Environmental Sciences, Leiden University, NL. Available: http://www.leidenuniv.nl/interfac/cml/ssp/projects/lca2/index.html.
COCKROFT, J. & KELLY, N. 2006. A comparative assessment of future heat and power sources for the UK domestic sector. *Energy Conversion and Management,* 47**,** 2349-2360.
COLANTONIO, A. 2009. Social sustainability - linking research to policy and practice. *Sustainable development - a challenge for European Research.* Brussels.
COLANTONIO, A. & DIXON, T. 2006. Defra Strategy Unit: input on defining 'social impacts'. Oxford: Oxford Institute for Sustainable Development (OISD), School of the Built Environment, Oxford Brookes University.
CONSERVATION, P. 2007. Community analysis package 4.0. Richard Seaby and Peter Henderson.
CONSUMERFOCUS 2009. A new energy infrastructure *Discussion paper by Prashant Vaze, Consumer Focus and Ed Mayo, Secretary General of Cooperatives UK*.
CORGI 2007. Gas in multi-occupancy dwellings.
CROXFORD, B. 2006. Gas appliance check project. London: Bartlett School of Graduate Studies - University College London.
CROXFORD, B., HUTCHINSON, E., LEONARDI, G., MCKENNA, L., NICHOLSON, L., VOLANS, G. & WILKINSON, P. 2006. Real time carbon monoxide measurements from 270 UK homes. Bartlett School of Graduate Studies, Medical Toxicology Unit, Guy's & St Thomas' Hospital, London School of Hygiene & Tropical Medicine, South London and Maudsley NHS Trust.
CROXFORD, B. & SCOTT, K. 2006. Can PV or solar thermal systems be cost effective ways of reducing CO2 emissions for residential buildings?
CRUMP, D., RAW, G., UPTON, S., SCIVYER, C., HUNTER, C. & HARTLESS, R. 2002. A protocal for the assessment of indoor air quality in homes and office buildings. London: BRE Office of the Deputy Prime Minister.
CSMHT 2010. Telecon with Tom Rock - City South Manchester Housing Trust Manchester.
DAY, A. R., JONES, P. G. & MAIDMENT, G. G. 2009. Forecasting future cooling demand in London. *Energy and Buildings,* 41**,** 942-948.
DCLG. 2013. *Live tables on household projections* [Online]. London. Available: https://www.gov.uk/government/statistical-data-sets/live-tables-on-household-projections [Accessed July 5th 2013].
DE ALMEIDA, A. T., LOPES, A., CARVALHO, A., MARIANO, J. & NUNES, C. 2004. Evaluation of fuel-switching opportunities in the residential sector. *Energy and Buildings,* 36**,** 195-203.
DECC. 2000. *CHPQA - Quality assurance for combined heat and power* [Online]. Department of energy and climate change. Available: http://chpqa.decc.gov.uk/ [Accessed November 26th 2013].

DECC 2008. Climate Change Act 2008 - Impact Assessment. *In:* CHANGE, D. O. E. A. C. (ed.).
DECC 2009a. CHPQA guidance note 10. London: Department of energy and climate change.
DECC 2009b. Energy consumption in the UK. *Department of energy and climate change, BERR and formally DTI*.
DECC 2009c. The Governments standard assessment procedure for energy rating of dwellings - 2005 edition revision 3. *In:* CHANGE, D. O. E. A. C. (ed.).
DECC 2009d. The UK Renewable Energy Strategy. London: Presented to Parliament by the Secretary of State for Energy and Climate Change by command of Her Majesty.
DECC 2009b. Energy trends - September 2009. *National Statistics*.
DECC 2009c. The UK Low Carbon Transition Plan - National strategy for climate and energy.
DECC 2010a. Digest of United Kingdom Energy Statistics. *In:* CHANGE, D. O. E. A. C. (ed.).
DECC 2010b. Energy Trends September 2010. *In:* CHANGE, D. O. E. A. C. (ed.). National Statistics.
DECC 2010c. Updated energy and emissions projections. *URN 10D/510.* Department of energy and climate change.
DECC 2010d. Warm Homes, Greener Homes: A Strategy for Household Energy Management. *In:* CHANGE, D. O. E. A. C. (ed.).
DECC 2011a. Connecting with communities - The Warm Front Scheme Annual Report 2010/2011. London: Department of energy and climate change.
DECC. 2011b. *Feed in tariffs* [Online]. Available: http://www.decc.gov.uk/en/content/cms/meeting_energy/Renewable_ener/feedin_tariff/feedin_tariff.aspx [Accessed November 6th 2011].
DECC. 2011c. *Green Deal* [Online]. London: Department of Energy and Climate Change. Available: http://www.decc.gov.uk/en/content/cms/tackling/green_deal/green_deal.aspx [Accessed 20th December 2011].
DECC. 2011d. *Standard assessment procedure (SAP)* [Online]. London: Department of Energy and Climate Change. Available: http://www.decc.gov.uk/en/content/cms/emissions/sap/sap.aspx [Accessed October 4th 2011].
DECC 2012a. DECC 2050 Pathways Calculator. London.
DECC 2012b. District heating - heat metering cost benefit analysis. London: Department of Energy and Climate Change.
DECC 2012c. The Future of Heating: A strategic framework for low carbon heat in the UK. *In:* CHANGE, D. O. E. C. (ed.). London.
DECC. 2013a. *CHP - Operations* [Online]. Available: http://chp.decc.gov.uk/cms/operation-maintenance/ [Accessed March 20th 2013 2013].
DECC 2013b. Digest of United Kingdom Energy Statistics 2012. *In:* CHANGE, D. O. E. C. (ed.). National Statistics.
DECC. 2013c. *Renewable Heat Incentive* [Online]. London. Available: http://chp.decc.gov.uk/cms/renewable-heat-incentive/ [Accessed June 3rd 2013].
DEFRA 2007a. Analysis of the UK potential for combined heat and power. London: DEFRA.

DEFRA 2007b. UK Biomass Strategy *In:* DEPARTMENT FOR ENVIRONMENT, F. A. R. A., LONDON (ed.).

DEFRA. 2010. *Resource recovery and recycling of materials from waste streams* [Online]. London: Department for Environment Food and Rural Affairs. Available: http://www.defra.gov.uk/evidence/statistics/environment/waste/wrferrous.htm [Accessed November 5th 2010 2010].

DIMPLEX 2009. Building for the future with Dimplex - Route One. Southampton: Dimplex Ltd.

DIMPLEX 2010. Dimplex domestic heating solutions. Southampton.

DIMPLEX 2011. Glen Dimplex response to DETI consultation on the development of the Northern Ireland Renewable Heat Incentive. Craigavon: Dimplex renewables.

DOSEWPC. 2011. *Nitrogen dioxide (NO2) - air quality fact sheet* [Online]. Australian government. Available: http://www.environment.gov.au/atmosphere/airquality/publications/nitrogendioxide.html [Accessed November 6th 2011].

DTI 2001. The UK Fuel Poverty Strategy. *In:* TEAM, D. O. T. A. I. F. P. (ed.).

DTI 2006a. Our Energy Challenge Power from the people - Microgeneration strategy. *Department of Trade and Industry*.

DTI 2006b. The Energy Challenge - A report.

DZIOUBINSKI, O. & CHIPMAN, R. 1999. Trends in consumption and production: Household energy consumption. New York: United Nations.

EAESL. 2010. *The encyclopaedia of alternative energy and sustainable living* [Online]. Available: http://www.daviddarling.info/encyclopedia/E/AE_electric_resistance_heating.html [Accessed November 4th 2010].

EC 1994. The Packaging and Packaging Waste Directive (94/62/EC). European Commission.

EC 2011.

ECI 2007. Is Electric Heating making a comeback? : European Copper Institute.

ECOINVENT 2008. EcoInvent data v 2.2 - Life Cycle Inventory Database.

ECOINVENT. 2010. *Organisation* [Online]. St-Gallen, Switzerland.

ECONNECT 2006. Accommodating Distributed Generation. London: Econnect Consulting.

ECUK 2013. Energy Consumption in the UK (2013). *In:* CHANGE, D. O. E. C. (ed.). London.

EEA 2008. Energy and environment report 2008. Copenhagen, Denmark: European Environment Agency.

EFRA 2006. Climate Change - The UK Programme 2006. *Presented to Parliament by the Secretary of State for the Environment, Food and Rural Affairs.*

EKINS-DAUKES, N. J. 2009. Solar energy for heat and electricity: the potential for mitigating climate change. London: Imperial College London.

ELEMENTENERGY 2008. The growth potential for Microgeneration in England, Wales and Scotland. Cambridge: Element Energy.

ELLIOTT, J. 2008. Guidance Note 3: Inspection & Testing, 5th Edition. *In:* ENGINEERS, I. O. E. (ed.). Institution of electrical engineers.

ENER, E. C. D. 2010. Preparatory studies for ecodesign requirements of EuPs (111) - ENER Lot 20, Local room heating products task 1: Definition.: European Commission.

ENERGY, C. F. S. 2010a. *Fuel Poverty Indicator* [Online]. Centre for sustainable energy - University of Bristol.

ENERGY, E. 2008. The growth potential for Microgeneration in England, Wales and Scotland.

ENERGY, T. 2010b. Feasibility study report - Coley high rise. *Work package 4.* Prepared for BioSol ESCo project.

ENERGYDESIGNTOOLS. 2010. *Standard assessment procedure - SAP* [Online]. Available: http://www.energydesigntools.co.uk/ [Accessed July 5th 2010].

ENERGYUK. 2013. *Fuel poverty* [Online]. Available: http://www.energy-uk.org.uk/policy/fuel-poverty.html [Accessed July 20th 2013].

ENERGYWATCH. 2011. *Paying for energy* [Online]. London: Energywatch - part of Consumer Focus. Available: http://www.consumerfocus.org.uk/policy-research/energy/paying-for-energy [Accessed December 3rd 2011].

ENGINEERLIVE. 2010. *Flat stations increase comfort and save heating energy* [Online]. London: Setform. Available: http://www.engineerlive.com/Energy-Solutions/Heat_Recovery/Flat_Stations_increase_comfort_and_save_heating_energy/21332/ [Accessed November 3rd 2010 2010].

ENSG 2009. Our Electricity Transmission Network: A vision for 2020. Electricity Networks Strategy Group.

ENVIROENERGY. 2013. *District Energy* [Online]. Available: http://www.enviroenergy.co.uk/district-energy/about-the-network/ [Accessed November 25th 2013].

EPA. 2013. *Combined heat and power partnership - basic information* [Online]. Available: http://www.epa.gov/chp/basic/ [Accessed May 30th 2013].

ERPT 2011. The future role for energy storage in the UK - Main report. London: Energy research partnership.

EST 2004. Community heating - a guide CE55. London: Energy saving trust.

EST 2006a. Domestic heating by electricity - 2006 edition. *In:* TRUST, E. S. (ed.).

EST 2006b. Integrating renewable energy into existing housing - case studies. *In:* TRUST, E. S. (ed.).

EST 2008. Power in numbers: the benefits and potential of distributed energy generation at the small community scale.

EST. 2010. *Carbon cuts get serious with CERT* [Online]. London: Energy Saving Trust. Available: http://www.energysavingtrust.org.uk/Easy-ways-to-stop-wasting-energy/Energy-saving-grants-and-offers/Carbon-cuts-get-serious-with-CERT [Accessed August 8th 2010].

EST. 2013. *Energy performance certificates* [Online]. Available: http://www.energysavingtrust.org.uk/Insulation/Energy-performance-certificates [Accessed June 15th 2013].

ETSU 1996. Good practice guide 176 - small-scale combined heat and power for buildings. ETSU.

EU 2003. DIRECTIVE 2002/96/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 27 January 2003 on waste electrical and electronic equipment (WEEE). *In:* UNION, E. (ed.).

EU 2008. DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. *In:* UNION, E. (ed.). Official journal of the European Union.

EU 2009. Renewable energy directive 2009. *In:* UNION, E. (ed.).

EVANS, A., STREZOV, V. & EVANS, T. J. 2009. Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews*, 13**,** 1082-1088.

FARNELL, P. 2010. The Eco-Design Directive.

FEI 2013. Comparison of Multi-Criteria Decision Analytical Software. Finnish Environment Institute - Jyri Mustajoki and Mika Marttunen.

FERREIRA, S. 2007. Gas heating verses electrical heating using different electricity mixes. Copper Institute.

FIADZOMOR, P., SIMS, R., DANIELS, S., AZAPAGIC, A. & PERSAUD, K. Indoor Air Quality Monitoring. Sustainable Cities, 2011 ARUP, London.

FLICK, U. 2002. *An introduction to qualitative research,* London, Sage.

FOREEST, F. V. 2011. Does natural gas need a decarbonisation strategy - The cases of the Netherlands and the UK. Oxford: The Oxford Institute for Energy Studies.

FORTMANN, R., KARIHER, P. & CLAYTON, R. 2001. Indoor air quality: residential cooking exposure. Report of "State of California Air Resources Board.

FOUNDATION, N. E. 2010. *Electric Night Storage Heaters* [Online]. Available: http://www.nef.org.uk/energysaving/storageheating.htm [Accessed November 3rd 2010 2010].

FULLER, H. B. S. 2012. Low carbon communities and social justice. Joseph Rowntree Foundation.

GASK, K. 2005. Population review of 2004 and 2005: England and Wales. *Office for National Statistics*.

GASSAFEREGISTER 2011. Landlords' gas safety responsibilities. *gassaferegister*. London.

GC 2008. Electric heating: not so virtuous! *Nuclear power: the great illusion.* Global Chance.

GED. 2010. *Solar thermal heating* [Online]. Green energy doctor. Available: http://www.greenenergydoctor.co.uk/solar-thermal-heating.php [Accessed October 28th 2010].

GERBER, A., AWAD, B., EKANAYAKE, J. B. & JENKINS, N. Operation of the 2030 GB power generation system. 2010. Institution of Civil Engineers.

GLASER, B. G. & STRAUSS, A. L. 1967. *The Discovery of Grounded Theory: Strategies for Qualitative Research*, Chicago, Aldine Publishing Company.

GLOBALCCS. 2012. *Barriers to implementation of CCS: capacity contraints* [Online]. Available: http://www.globalccsinstitute.com/publications/barriers-implementation-ccs-capacity-constraints/online/106091 [Accessed November 25th 2013].

GMEC. 2013. *Greater Manchester District Heat Networks* [Online]. Manchester: Greater Manchester Environment Commission. Available: http://media.ontheplatform.org.uk/sites/default/files/district_heat_spreads_0.pdf [Accessed November 25th 2013].

GOVERNMENT, S. 2008. The Scottish Renewables Heating Pilot. *In:* RESEARCH, S. (ed.).

GRID, N. 2011. *Calorific value description* [Online]. Available: http://www.nationalgrid.com/uk/Gas/Data/misc/reports/description/.

GRID, N. 2012. *Grid @75* [Online]. Warwick: National Grid. Available: http://www.nationalgrid75.com/timeline [Accessed January 2nd 2012].

GSHPA. 2010. *Ground source heat pumps* [Online]. Ground source heat pump association. Available: http://www.gshp.org.uk/faqs.htm [Accessed October 22nd 2010].

GSR. 2011. *Information for landlords - gas safety checks* [Online]. London: Gas safety register. Available: http://www.gassaferegister.co.uk/advice/renting_a_property/for_landlords.aspx [Accessed September 20th 2011].

GUERTLER, P. & SMITH, W. 2006. Energy Efficiency in the Refurbishment of High-Rise Residential Buildings - Final Report. London: Association for the Conservation of Energy.

GUSTAVSSON, L. & JOELSSON, A. 2008. Life cycle primary energy analysis of residential buildings. *Energy and Buildings,* 42**,** 210-220.

HALCROW, G. L. 2008. Heat Mapping and Decentralised Energy Feasibility Study Phase 1: Data Gathering and Mapping *A Report for 'Advantage West Midlands'*.

HARRISON, G. P., MACLEAN, E. J., KARAMANLIS, S. & OCHOA, L. F. 2010. Life cycle assessment of the transmission network in Great Britain. *Energy Policy,* 38**,** 3622-3631.

HARVEY, D. 2006. A Handbook on Low-Energy Buildings and District-Energy Systems: Fundamentals, Techniques and Examples. *Earthscan Ltd; illustrated edition (1 Aug 2006)*

HEATANDPLUMB. 2010. *Central heating boilers project* [Online]. Available: http://www.diydoctor.org.uk/projects/boilers.htm [Accessed September 13th 2010].

HENDERSON, J. & YOUNG, B. 2008. Domestic heating systems ranked by carbon emissions version 2. *In:* TRUST, P. F. T. E. S. (ed.).

HILL, M. 2010. *Types of boiler* [Online]. London. Available: http://www.muswell-hill.com/foxandco/pages/boilertypes.htm [Accessed 20th October 2010. 2010].

HILLS, J. 2011. Fuel poverty - The problem and its management. *In:* REPORT, H. F. P. R.-I. (ed.).

HMGOV 2010. Approved document F1 - Means of ventilation. *In:* REGULATIONS, T. B. (ed.).

HMGOV 2011. The Carbon Plan: Delivering our low carbon future. London: DECC - Department of energy and climate change.

HMGOVERNMENT. 2000. *Warm Homes and Energy Conservation Act 2000* [Online]. London: HM Government legislation.gov.uk. Available: http://www.legislation.gov.uk/ukpga/2000/31 [Accessed November 23rd 2010].

HOC 2010. Beyond decent homes - 4th report of session 2009-2010. House of Commons Communities and Local Government Committee.

HODGSON, P. 2004. Gas supplies to the UK - a review of the future. *Institute of physics*.

HOLLOWAY, S. & ROWLEY, W. J. 2008. Environmental sustainability of electricity generation systems with carbon dioxide capture and storage - working paper. London: The UK Energy Research Centre.

HONG, S. H., GILBERTSON, J., ORESZCZYN, T., GREEN, G. & RIDLEY, I. 2009. A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. *Building and Environment,* 44**,** 1228-1236.

HOP 2004. The future of UK gas supplies - postnote 230. *Parliamentary office of science and technology*.

HSE 2009. Landlords - A guide to landlords’ duties: Gas Safety (Installation and Use) Regulations 1998. London: Health and safety executive.

HSE. 2010. *Gas health and safety law and enforcement* [Online]. London. Available: http://www.hse.gov.uk/gas/domestic/gas_law.htm [Accessed May 8th 2010].

HUTCHINS 2010a. *The small works and maintenance construction cost guide - Volume 1,* London, Price books.

HUTCHINS 2010b. *UK Building Blackbook - the capital cost and embodied CO2 guide - volume 2,* London, Price books.

IBM. 2013. *SPSS software* [Online]. Available: http://www-01.ibm.com/software/uk/analytics/spss/ [Accessed July 28th 2013].

ICARO 2009. Understanding Consumer Attitudes to "Sustainable Community Infrastructure". Research for UK Green Building Council and Carbon Hub.

ICEPT & CES 2010. Building a roadmap for heat 2050 scenarios and heat delivery in the UK. University of Surrey and Imperial College London.

IEA 2004. Urban community heating and cooling: the Southampton district energy scheme. Southampton: International Energy Association.

IEA 2005. A comparison of distributed CHP/DH with large-scale CHP/DH. International Energy Agency.

IEA 2008. Key world energy statistics. Paris: International energy agency.

IEA 2010a. SOLAR HEAT FOR INDUSTRIAL PROCESSES. *Detailed papers to Newsletter No. 1.* International energy agency.

IEA 2010b. Solar Sustainable Housing - Project Summary Report. *ECBCS Annex 38 / SHC Task 28.* International Energy Agency.

IEA 2011. Technology roadmap - Energy-efficient buildings: heating and cooling equipment. Paris: International Energy Agency.

IEE 2008. Code of practice for in-service inspection and testing of electrical equipment - 3rd edition. Institution of Electrical Engineers.

IGEM 2006. General gas procedures - IGEM commentary on amendments to IGE/G/5 - Gas in flats and other multi-dwelling buildings. *In:* MANAGERS, I. O. G. E. A. (ed.). IGEM.

INTERNATIONAL, Q. 2011. *NVIVO* [Online]. Available: http://www.qsrinternational.com/products_nvivo.aspx [Accessed June 5th 2011].

INTERPON. 2013. *Powder coatings* [Online]. Interpon - AkzoNobel. Available: http://www.interpon.com/our-coatings/powder-finder/powder-detail/2/?powder_code=EA192D [Accessed August 2013.

IPCC. 2007. *Climate change 2007: Working group III: Mitigation of climate change - combined heat and power (CHP)* [Online]. Available: http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch4s4-3-5.html.

ISO 2006a. ISO 14040 - Environmental Management - Life Cycle Assessment - Principles and Framework. Geneva.

ISO 2006b. ISO 14040: 2006. International Organization for Standardization.

ISO 2006c. ISO 14044 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines. Geneva.

JARNSTROM, H., SAARELA, K., KALLIOKOSKI, P. & PASANEN, A. L. 2006. Reference values for indoor air pollutant concentrations in new, residential buildings in Finland. *Atmospheric Environment,* 40**,** 7178-7191.

JEC. 2009. *Use less Imported Energy* [Online]. St Helier: Jersey Electricity Company.

JEC. 2010. *Environmental Credentials of Electricity* [Online]. St Helier: Jersey Electricity Available: http://www.jec.co.uk/environment/ [Accessed August 2nd 2010].

JIA, C., BATTERMAN, S. & GODWIN, C. 2008. VOCs in industrial, urban and suburban neighborhoods Part 2: Factors affecting indoor and outdoor concentrations. *Atmospheric Environment,* 42**,** 2101-2116.

JONES, A., AUSTIN, J., BRIMBLECOMBE, P. & STURGES, W. 2002. Chapter 3 Indoor air quality and health. *Developments in Environmental Sciences.* Elsevier.

KALOGIROU, S. A. 2004. Environmental benefits of domestic solar energy systems. *Energy Conversion and Management,* 45**,** 3075-3092.

KANE, T., FIRTH, S. K., LOMAS, K. J., ALLINSON, D. & IRVINE, K. 2011. Variation of indoor temperatures and heating practices in UK dwellings. Loughborough University and De Montfort University.

KATSOUYANNI, K., TOULOUMI, G., SPIX, C., SCHWARTZ, J., BALDUCCI, F., MEDINA, S., ROSSI, G., WOJTYNIAK, B., SUNYER, J., BACHAROVA, L., SCHOUTEN, J. P., PONKA, A. & ANDERSON, H. R. 1997. Short term effects of ambient sulphur dioxide and particulate matter on mortality in 12 European cities: results from time series data from the APHEA project. *British Medical Journal*.

KLUNKLIN, A. & GREENWOOD, J. 2006. Symbolic Interactionism in Grounded Theory Studies: Women Surviving With HIV/AIDS in Rural Northern Thailand. *Journal of the Association of Nurses in AIDS care,* 17**,** 32-41.

KORNARTIT, C., SOKHI, R. S., BURTON, M. A. & RAVINDRA, K. 2010. Activity pattern and personal exposure to nitrogen dioxide in indoor and outdoor microenvironments. *Environment International,* 36**,** 36-45.

KORONEOS, C. & DOMPROS, A. 2007. Environmental assessment of brick production in Greece. *Building and Environment,* 42**,** 2114-2123.

LATZA, U., GERDES, S. & BAUR, X. 2009. Effects of nitrogen dioxide on human health: Systematic review of experimental and epidemiological studies conducted between 2002 and 2006. *International Journal of Hygiene and Environmental Health,* 212**,** 271-287.

LAZARUS, N. 2003. BedZED: Toolkit Part II - A practical guide to producing affordable carbon neutral developments. Wallington, Surrey: BioRegional.

LEIDL, C. M. & DAVID LUBITZ, W. 2009. Comparing domestic water heating technologies. *Technology in Society,* 31**,** 244-256.

LEP 2006. London Carbon Scenarios to 2026. London: London Energy Partnership.

LEP 2007. Making ESCO's work: guidance and advice on setting up and delivering an ESCO. London Energy Partnership.

LEVINE, M., ÜRGE-VORSATZ, D., BLOK, K., GENG, L., HARVEY, D., LANG, S., LEVERMORE, G., MEHLWANA, A. M., MIRASGEDIS, S., NOVIKOVA, A., RILLING, J. & YOSHINO, H. 2007. Residential and commercial buildings. Cambridge IPCC.

LINKOV, I. & RAMADAN, A. B. 2004. *Comparative risk assessment and environmental decision making,* Springer Science.

LUICKX, P. J., HELSEN, L. M. & D'HAESELEER, W. D. 2008. Influence of massive heat-pump introduction on the electricity-generation mix and the GHG effect: Comparison between Belgium, France, Germany and The Netherlands. *Renewable & Sustainable Energy Reviews,* 12**,** 2140-2158.

LUND, H., MÖLLER, B., MATHIESEN, B. V. & DYRELUND, A. 2010. The role of district heating in future renewable energy systems. *Energy,* 35**,** 1381-1390.

MACKAY, D. J. C. 2008. Sustainable Energy - without the hot air - synopsis. *Sustainable Energy - without the hot air*.

MANDAL, S., RUGGLES, R., LEONARDI, G., GOODFELLOW, F., BRADLEY, N. & MURRAY, V. 2010. Developing best practice response to carbon monoxide incidents: A toolkit for health protection frontline staff. *Public Health,* 125**,** 148-156.

MANFREN, M., CAPUTO, P. & COSTA, G. 2010. Paradigm shift in urban energy systems through distributed generation: Methods and models. *Applied Energy,* 88**,** 1032-1048.

MARKKU, L. 2004. The environmental-social interface of sustainable development: capabilities, social capital, institutions. *Ecological Economics,* 49**,** 199-214.

MCKEGANEY, N. P. 1995. Quantitative and qualitative research in the addictions: an unhelpful divide. *Addiction***,** 749-751.

MHS 2010. Guide to Apartment Heating. London: MHS boilers.

MICANOVIC, S. & BRINCKERHOFF, P. 2012. *Decoupling demands - thermal stores for CHP* [Online]. CIBSE. Available: http://www.cibse.org/content/Groups/Building_Simulation_Group/Decoupling%20demands%20-Thermal%20stores%20for%20CHP.pdf. [Accessed September 3rd 2013].

MILLER, G. T. 2005. *Living in the environment,* CA, Thomson.

MÖLLER, B. & LUND, H. 2010. Conversion of individual natural gas to district heating: Geographical studies of supply costs and consequences for the Danish energy system. *Applied Energy,* 87**,** 1846-1857.

MONAHAN, J. & POWELL, J. C. 2010. A comparison of the energy and carbon implications of new systems of energy provision in new build housing in the UK. *Energy Policy,* 39**,** 290-298.

MOORE, R. 2005. The fall and rise of fuel prices and fuel poverty. London: Energywatch, UNISON, Parliamentary Warm Homes Group, .

MTMW. 2011. *Making the modern world* [Online]. Making the modern world. Available: http://www.makingthemodernworld.org.uk/stories/the_rise_of_consumerism/02.ST.03/?scene=3 [Accessed December 15th 2011].

MTP 2007. BNCK01: Assumptions underlying the energy projections of cooking appliances. Briefing note ed.: Market transformation programme.

MUSTAFA OMER, A. 2008. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews,* 12**,** 344-371.

MYERS, P. 2004. *Sustaining: tower blocks* [Online]. London: Price & Myers Sustainability.

NAMIESNIK, J., GORECKI, T., LA, K.-Z. & LUKASIAK, J. 1992. Indoor air quality (IAQ), pollutants, their sources and concentration levels. *Building and Environment,* 27**,** 339-356.

NAO 2009. The Warm Front Scheme. *In:* OFFICE, N. A. (ed.).

NATGAS. 15 September 2011 2011. *RE: Natural Gas composition.*

NATIONALGRID 2009a. Gas Transportation Ten Year Statement 2009. London: National Grid UK.

NATIONALGRID 2009b. The potential for Renewable Gas in the UK.

NATIONALGRID 2010. Telecon with Johnny Johnston - National Grid UK, Network Planning Manager. Manchester.

NATIONALGRID 2011. UK Future Energy Scenarios. National Grid.

NATIONALGRID. 2013. *Calorific value description* [Online]. UK. [Accessed July 6th 2013].

NATIONWIDE. 2008. *House prices - special feature 4: Flats* [Online]. Nationwide building society. Available:

http://www.nationwide.co.uk/NR/rdonlyres/B220A473-CEEB-4646-9B4F-6004130F4179/0/Flats.pdf [Accessed June 20th 2013].
NEEDS 2006. Energy technology roadmap and stakeholders perspective "Establishment of social criteria for energy systems". Updated report on social indicators accommodating Delphi results. Stuttgart: New Energy Externalities Developments for Sustainability.
NERA & AEA 2009. The UK Supply Curve for Renewable Heat Study. *Department of Energy and Climate Change*.
NERA, A. A. 2009. The Supply Curve for Renewable Heat - Overview of Research. *PPT*.
NRC 2003. Heating With Electricity. Natural Resources Canada - Office of Energy Efficiency.
NSO 2001. The definition of urban areas. *In:* OFFICE, N. S. (ed.).
ODEH, N. A. & COCKERILL, T. T. 2008. Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy,* 36**,** 367-380.
ODPM 2004a. The Egan Review - skills for sustainable communities.
ODPM 2004b. The Egan Review: Skills for Sustainable Communities - ANNEX B: SUSTAINABLE COMMUNITIES INDICATORS.
ODPM 2004c. Planning policy statement 22: Renewable Energy. *Office of the Deputy Prime Minister*.
ODPM 2005. Planning policy statement - delivering sustainable development. *In:* MINISTER, O. O. T. D. P. (ed.). ODPM.
ODPM 2006a. Building regulations 2000 - Conservation of fuel and power in new dwellings, L1A. *Office of the deputy prime minister.*
ODPM 2006b. Conservation of fuel and power in existing dwellings L1B. London: Office of the Deputy Prime Minister.
ODPM 2006c. Conservation of fuel and power in new dwellings L1B London: Office of the Deputy Prime Minister.
OECD/IEA 2011. Evaluating the co-benefits of low-income energy-efficiency programmes. International Energy Agency.
OFGEM 2009. Sustainable Development Report 2008/09.
OFGEM. 2010a. *Grid electricity generation efficiency* [Online]. London.
OFGEM 2010b. Renewables Obligation: Annual Report 2008-2009. *In:* MARKETS, O. O. G. A. E. (ed.). OFGEM.
OFGEM 2011. Electricity and gas supply market report. London: OFGEM.
OFGEM. 2013. *Electricity interconnectors* [Online]. London. Available: https://www.ofgem.gov.uk/electricity/transmission-networks/electricity-interconnectors [Accessed October 13th 2013].
OLIVER-SOLÀ, J., GABARRELL, X. & RIERADEVALL, J. 2009. Environmental impacts of the infrastructure for district heating in urban neighbourhoods. *Energy Policy,* 37**,** 4711-4719.
OLIVIER, D. 2007. The Green Energy Illusion - Technical paper Version 1.0.0. *AECB strategic guidance - Carbon Lite programme*.
OLSON, D. A. & BURKE, J. M. 2006. Distributions of PM2.5 source strengths for cooking from the Research Triangle Park particulate matter panel study. *Environ.Sci. Technol., 40, 163-169.*
ONS. 2011. *Population Estimates for UK, England and Wales, Scotland and Northern Ireland, Mid-2010* [Online]. London: Office for National Statistics. Available: http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-231847 [Accessed November 25th 2011].

OPSI 2008. Climate Change Act 2008 (Chapter 27). London: Office of Public Sector Information.

ORTIZ, O., CASTELLS, F. & SONNEMANN, G. 2009. Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 23**,** 28-39.

PAPADOPOULO, M., KADDOUH, S., CIGNI, A., GULLENTOPS, D., SERINA, S., VORGANG, J., VEENSTRA, T. & DUPIN, F. 2009. Life Cycle Assessment of the European Natural Gas Chain - A Eurogas - Marcogaz Study. *International Gas Union*.

PARADISEWHARF. 2010. *Apartments in Manchester* [Online]. Manchester. Available: WWW.APARTMENTS-MANCHESTER.CO.UK [Accessed September 5th 2010].

PARRA, M. A., ELUSTONDO, D., BERMEJO, R. & SANTAMARÃ-A, J. M. 2008. Quantification of indoor and outdoor volatile organic compounds (VOCs) in pubs and cafÃ©s in Pamplona, Spain. *Atmospheric Environment*, 42**,** 6647-6654.

PAUL S, H. 1987. Occult carbon monoxide poisoning: A cause of winter headache. *The American Journal of Emergency Medicine*, 5**,** 201-204.

PE. 2010. *GaBi Software* [Online]. Available: http://www.pe-international.com/index.php?id=152&L=19&redirect=1 [Accessed November 26th 2010].

PEINTERNATIONAL 2009. Handbook for Life Cycle Assessment (LCA) - Using the GaBi Education Software Package. Germany: PE International

POINTER, G. 2005. The UK's major urban areas. *Focus on People and Migration - Chapter 3*. National Statistics Office.

POWER, P. 2004. The Cost of Generating Electricity. London The Royal Academy of Engineering.

POYRY, MAUNSELL, F. & AECOM 2009. The potential and costs of district heating networks. London: A report to the DECC.

PREK, M. 2004. Environmental impact and life cycle assessment of heating and air conditioning systems, a simplified case study. *Energy and Buildings*, 36**,** 1021-1027.

QDATRAINING. 2013. *Defining the constant comparative method* [Online]. Available: http://www.qdatraining.eu/content/defining-constant-comparative-method [Accessed December 5th 2013].

QUALTRICS. 2011. *Online surveys* [Online]. Available: http://www.qualtrics.com/ [Accessed March 5th 2011].

QUANTUM 2008. Low Carbon Energy Market Survey. Manchester: Quantum Strategy and Technology for Electricity NorthWest.

QUARTZSTAR 2010. OnBalance. Edinburgh Quartzstar Software Ltd.

RAUB, J. A., MATHIEU-NOLF, M., HAMPSON, N. B. & THOM, S. R. 2000. Carbon monoxide poisoning - a public health perspective. *Toxicology*, 145**,** 1-14.

REALTIME. 2011. *Realtime carbon* [Online]. Available: http://realtimecarbon.org/ [Accessed July 5th 2011 2011].

RIMMER, D. 2012a. *National Grid - Expert Pathway* [Online]. National Grid, Energy Scenarios Manager: National Grid. [Accessed November 25th 2012].

RIMMER, D. 2012b. *National Grid: Mix of CCS, nuclear, renewables and all cars electrified* [Online]. London DECC. Available: http://blog.decc.gov.uk/duncan-rimmer-national-grid-mix-of-ccs-nuclear-renewables-and-all-cars-electrified/ [Accessed December 5th 2012].

RIVA, A., D'ANGELOSANTE, S. & TREBESCHI, C. 2006. Natural gas and the environmental results of life cycle assessment. *Energy,* 31**,** 138-148.

ROBERTS, S. 2008. Infrastructure challenges for the built environment. *Energy Policy,* 36**,** 4563-4567.

ROTH, S., HIRSCHBERG, S., BAUER, C., BURGHERR, P., DONES, R., HECK, T. & SCHENLER, W. 2009. Sustainability of electricity supply technology portfolio. *Annals of Nuclear Energy,* 36**,** 409-416.

SACHS, I. 1999. *Social sustainability and whole development: exploring the dimensions of sustainable development,* Paris, Zed Books.

SANER, D., JURASKE, R., KÜBERT, M., BLUM, P., HELLWEG, S. & BAYER, P. 2010. Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems. *Renewable and Sustainable Energy Reviews,* 14**,** 1798-1813.

SASNAUSKAITE, V., UZSILAITYTE, L. & ROGOZA, A. 2007. A sustainable analysis of a detached house heating system throughout its life cycle. A case study.(Case study). *International Journal of Strategic Property Management*

SCC. 2013. *Geothermal and CHP scheme* [Online]. Southampton City Council. Available: http://www.southampton.gov.uk/s-environment/energy/Geothermal/ [Accessed November 23rd 2013].

SCHLINK, U., THIEM, A., KOHAJDA, T., RICHTER, M. & STREBEL, K. 2010. Quantile regression of indoor air concentrations of volatile organic compounds (VOC). *Science of The Total Environment,* 408**,** 3840-3851.

SEDBUK. 2010. *Boiler efficiency database* [Online]. Available: http://www.sedbuk.com/ [Accessed August 11th 2010].

SES. 2010. *Basic facts about renewables* [Online]. London: The Solar Energy Society. Available: http://www.uk-ises.org/facts_sheet.htm [Accessed May 8th 2010].

SHAH, V. P., DEBELLA, D. C. & RIES, R. J. 2008. Life cycle assessment of residential heating and cooling systems in four regions in the United States. *Energy and Buildings,* 40**,** 503-513.

SHORROCK, J. I. U. A. L. D. 2008. Domestic Energy Factfile 2008. *BRE Energy Saving Trust and DECC.*

SIMS, R. 2011. Manchester city centre apartment block heating desktop survey. Manchester The University of Manchester.

SKM 2008. Growth scenarios for UK renewables generation and implications for future developments and operation of electricity networks. Sinclair Knight Merz.

SOLARUK 2005. Killick House, Sutton: The UK's largest domestic vacuum solar thermal installation. London: Solar UK.

SPON'S 2010a. *Civil Engineering and Highway Works Price Book,* London, Taylor and Francis.

SPON'S 2010b. *Mechanical and Electrical Services Price Book 2010,* London, Taylor and Francis.

SPON'S 2012. *Mechanical and electrical services price book 2012*, Davis Langdon.

SPRING 2011a. Assessing the sustainability of nuclear power in the UK. Manchester: The University of Manchester - SPRIng project.

SPRING 2011b. ETLCA SPRIng Scenarios. Sustainable Industrial Systems.

STAMFORD, L. & AZAPAGIC, A. 2011. Sustainability indicators for the assessment of nuclear power. *Energy,* 36**,** 6037-6057.

STELRAD. 2010. *Heatloss and U value calculator* [Online]. Rotherham. Available: http://www.stelrad.com/UK/stars.html [Accessed July 18th 2010].

STRACHAN, N. & KANNAN, R. 2007. Final report on DTI-DEFRA scenarios and sensitivities, using the UK markal and markal-macro energy system models. *In:* CENTRE, U. E. R. (ed.). Policy Studies Institute.

STRANGER, M., POTGIETER-VERMAAK, S. S. & VAN GRIEKEN, R. 2009. Particulate matter and gaseous pollutants in residences in Antwerp, Belgium. *Science of The Total Environment*, 407**,** 1182-1192.

STRAUSS, A. & CORBIN, J. 1998. *Basics of qualitative research: Techniques and procedures for developing grounded theory*, SAGE publications.

THYHOLT, M. & HESTNES, A. G. 2008. Heat supply to low-energy buildings in district heating areas: Analyses of CO_2 emissions and electricity supply security. *Energy and Buildings,* 40**,** 131-139.

TOKE, D. & FRAGAKI, A. 2008. Do liberalised electricity markets help or hinder CHP and district heating? The case of the UK. *Energy Policy,* 36**,** 1448-1456.

TOREKOV, M., BAHNSEN N, QVALE B,. 2007. The relative competitive positions of the alternative means for domestic heating. *Energy,* 32**,** 627-633.

TURTON, H. & BARRETO, L. 2006. Long-term security of energy supply and climate change. *Energy Policy,* 34**,** 2232-2250.

UKERC 2009a. Decarbonising the UK Energy System: Accelerated Development of Low Carbon Energy Supply Technologies. *UKERC Energy 2050 Research Report No. 2*.

UKERC 2009b. Making the transition to a secure and low-carbon energy system: synthesis report.

UKGBC 2010. Sustainable community infrastructure-Executive Summary. UK Green Building Council, Zero Carbon Hub.

UKGOV 2005. The Hazardous Waste (England and Wales) Regulations 2005. Government legislation UK

UKPOWER. 2010. *Economy 10 and Economy 7 electricity heating tariff* [Online]. Available: http://www.ukpower.co.uk/home_energy/economy_10 [Accessed September 14th 2010].

VALLANCE, S., PERKINS, H. C. & DIXON, J. E. 2011. What is social sustainability? A clarification of concepts. *Geoforum,* 42**,** 342-348.

VANCLAY, F. 2003. Conceptual and methodological advances in social impact assessment. *In: H.A. Becker and F. Vanclay, Editors, The international handbook of social impact assessment-conceptual and methodological advances Edward Elgar.*

VEOLIA. 2013. *Pipe in the potential - District Energy* [Online]. Available: http://www.veoliaenvironmentalservices.co.uk/Sheffield/What-happens-to-your-waste/District-Energy/ [Accessed November 24th 2013].

VICKERY-NIEDERMAN, C. B. G. 2010. Social Sustainability Assessment Literature Review MEASUREMENT SCIENCE. Sustainability consortium - Arizona State University and University of Arkansas.

VIESSMANN 2008. Why use Solar Energy? - Case Study Examples. London: Viessmann solar thermal manufacturers.

VIESSMANN. 2010. *Heating system components* [Online]. Allendorf. Available: http://www.viessmann.com/com/etc/medialib/internet-global/pdf_documents/com/brochures_englisch.Par.3927.File.File.tmp/ppr-vitoset.pdf [Accessed September 30th 2010].

WCED 1987. *Our common future,* Oxford, Oxford University Press.

WHO 2000. Air Quality Guidelines for Europe World Health Organization Regional Office for Europe Copenhagen WHO Regional Publications, European Series, No. 91 Second Edition. *WHO Regional Publications, European Series, No. 91*.

WHO 2010. WHO guidelines for indoor air quality: selected pollutants. Copenhagen, Denmark: World Health Organisation.

WHO. 2011. *Air quality and health* [Online]. Copenhagen. Available: http://www.who.int/mediacentre/factsheets/fs313/en/index.html [Accessed October 3rd 2011].

WILKINSON, C. 2005. Skyscrapper news. London: Skyscrappernews.com.

WILTSHIRE, R. 2005. District heating and cooling including the integration of CHP. Available: http://www.iea-dhc.org/annexvii/0%20introduction%20by%20chairman.ppt.

WINKLE, M. R. & SCHEFF, P. A. 2001. Volatile Organic Compounds, Polycyclic Aromatic Hydrocarbons and Elements in the Air of Ten Urban Homes. *Indoor Air*, 11**,** pages 49-64.

WINSKEL, M. 2002. When Systems are Overthrown The `Dash for Gas' in the British Electricity Supply Industry. *Social Studies of Science*.

WPD 2004. Housing Development design framework - ENA Engineering Recommendation G81. *In:* DISTRIBUTION, W. P. (ed.).

Appendices

11 Appendix 1: Common sources of pollutants and guidelines on concentrations and durations of pollutants for the indoor environment

11.1 Sources of common relevant pollutants in the indoor environment (Maroni et al., 1995) from (Jones et al., 2002).

Pollutant	Source	Examples of typical contaminants
Volatile organic components (VOCs)	Consumer and commercial products	Aliphatic hydrocarbons (n-decane, branched alkanes), aromatic hydrocarbons (toluene, xylenes), halogenated hydrocarbons (methylene chloride), alcohols, ketones (acetone, methyl ethyl ketone), aldehydes (formaldehyde), esters (alkyl ethoxylate), ethers (glycol ethers), terpenes (limonene, alpha-pinene).
	Furnishings and clothing	Aromatic hydrocarbons (styrene, brominated aromatics), halogenated hydrocarbons (vinyl chloride), aldehydes (formaldehyde), ethers, esters.
	Combustion appliances	Aliphatic hydrocarbons (propane, butane, isobutane), aldehydes (acetaldehyde, acrolein).
	Potable water	Halogenated hydrocarbons (1,1,1-trichloroethane, chloroform, trichloroethane)
CO	Combustion appliance, tobacco smoke and vehicle exhausts	
SO_2	Burning of sulphur from coal, crude oil, wool, hair, foam rubber and tyres	
NO_2	Burning of fossil fuels – gas, coal, vehicle fumes and gas stoves and heaters	Too much air in combustion can produce Nitrogen oxides
CO_2	Humans, combustion	

11.2 Indoor pollutants guidelines.

Gas	Guideline	Concentration	Supporting details
VOCs	Building regulations, part F (HMGOV, 2010)	VOCs ≤ 300µg m³ - 8 hours averaging time	
CO	WHO (WHO, 2010)	15 minutes – 100 mg/m^3 1 hour – 35 mg/m^3 8 hours – 10 mg/m^3 24 hours – 7 mg/m^3	Typical exposures: Acute exposure-related reduction of exercise tolerance and increase in symptoms of ischaemic heart disease (e.g. ST-segment changes).
SO_2	WHO (WHO, 2010)	20 $\mu g/m^3$ 24-hour mean 500 $\mu g/m^3$ 10-minute mean	A SO_2 concentration of 500 $\mu g/m^3$ should not be exceeded over average periods of 10 minutes duration.

			SO_2 is a colourless gas with a sharp odour. It is produced from the burning of fossil fuels (coal and oil) and the smelting of mineral ores that contain sulphur. The main anthropogenic source of SO_2 is the burning of sulphur-containing fossil fuels for domestic heating, power generation and motor vehicles. SO_2 can affect the respiratory system and the functions of the lungs, and causes irritation of the eyes.
NO_2	WHO (WHO, 2010)	200 µg/m^3 – 1 hour average 40 µg/m^3 – annual average	Road traffic is the principal outdoor source of nitrogen dioxide. The most important indoor sources include tobacco smoke and gas-, wood-, oil-, kerosene- and coal-burning appliances such as stoves, ovens, space and water heaters and fireplaces, particularly un-flued or poorly maintained appliances. Respiratory symptoms, bronchoconstriction, increased bronchial reactivity, airway inflammation and decreases in immune defence, leading to increased susceptibility to respiratory infection
CO_2	ASHRAE (ASHRAE, 2010)	No specific limits but levels greater than 5 000 ppm pose a health risk. Others suggest levels above 1000 ppm indicate inadequate ventilation.	CO_2 levels can be regarded as an indicator of occupant odour with high levels of CO_2 causing drowsiness, headaches and lower activity levels. Increased levels can also be associated with the combustion of fuels.

12 Appendix 2: Description of life cycle assessment (LCA)

12.1 Standards and process

There are two LCA standards created by the International Organization for Standardization (ISO) – the ISO 14040 and ISO 14044. Life cycle assessment can be defined as the 'compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle' (PEInternational, 2009).

LCA can be used to establish the environmental burdens associated with a product or service and thus help identify potential pathways for improving environmental sustainability. It can be used to assist with decision making and select relevant indicators of environmental performance. An LCA study comprises of four phases according to ISO (ISO, 2006a; ISO, 2006c):

1) *Goal and scope definition* – the aims of the study are outlined along with the system boundaries and the intended audience. The functional unit, defining the system under study are also detailed;
2) *Inventory analysis* – inputs and outputs and the potential environmental impacts regarding the studied systems are compiled;
3) *Impact assessment* – in this phase, the inventory analysis results are associated to specific environmental impacts in order to understand their significance. This phase can be subdivided into elements – classification, characterisation, normalisation and valuation;
4) *Interpretation* – the final phase are where the results of the study are summarised and discussed to produce conclusions, recommendations and decision in accordance with the original study goal. In addition, areas of potential improvement are also identified.

12.2 Life cycle environmental impact indicators.

Indicator	Definition
Abiotic resource depletion (ADP elements) [kg Sb-Equiv.]	Refers to the exhaustion of natural resources such as iron ore or copper
Abiotic resource depletion (ADP fossil) [MJ]	Refers to the exhaustion of natural resources such as gas, coal etc.

Acidification Potential (AP) [kg SO2-Equiv.]	Contribution to acid deposition
Eutrophication potential (EP) [kg Phosphate-Equiv.]	Potential to cause over fertilisation of the water and soil
Freshwater aquatic eco-toxicity potential (FAETP) [kg Dichlorobenzene (DCB) –Equiv.]	Toxic releases to freshwater environment
Global warming potential (GWP) [kg CO2-Equiv.]	Potential contribution to Climate Change
Human toxicity potential (HTP) [kg DCB-equiv.]	Human toxic releases to air, water and soil
Marine aquatic eco-toxicity potential(MAETP) [kg DCB-equiv.]	Toxic releases to marine environment
Ozone layer depletion potential (ODP) [kg R11-Equiv.]	Contribution to ozone depletion
Photochemical ozone creation potential (POCP) [kg Ethane-equiv.]	Contribution to photo-oxidant formation
Terrestrial eco-toxicity potential(TETP) [kg DCB-Equiv.]	Toxic releases to terrestrial environment

13 Appendix 3: Social sustainability

13.1 Online questionnaire using Qualtrics.

1. INTRODUCTION Welcome to the research into Modal Switching ……..

Statistic	I have read and understood the survey introduction and Participant Information (FAQ) Sheet and agree to take part in this survey questionnaire on a voluntary basis.
Min Value	1
Max Value	1
Mean	1.00
Variance	0.00
Standard Deviation	0.00
Total Responses	231

2. Here we go! This section of the questionnaire provides a perspective as to why the householder is currently living in this particular property. Did any of the following factors influence you when you bought or rented this property? (tick one box for each item)

#	Question	Strongly influenced	Some influence	No influence	Responses	Mean
1	The type of heating system installed	17	45	154	216	2.63
2	Location of the apartment block	119	93	9	221	1.50
3	Rent or purchase price	130	81	10	221	1.46
4	Transport connections	82	122	16	220	1.70
5	Friends/relatives living nearby	23	125	72	220	2.22
6	Allocation of the housing by the council or housing agency	53	28	139	220	2.39
7	Reputation of the area	37	126	57	220	2.09
8	Other (please specify)	12	5	26	43	2.33

Statistic	The type of heating system installed	Location of the apartment block	Rent or purchase price	Transport connections	Friends/relatives living nearby	Allocation of the housing by the council or housing agency	Reputation of the area	Other (please specify)
Min Value	1	1	1	1	1	1	1	1
Max Value	3	3	3	3	3	3	3	3
Mean	2.63	1.50	1.46	1.70	2.22	2.39	2.09	2.33
Variance	0.39	0.33	0.34	0.36	0.38	0.72	0.42	1.44
Standard Deviation	0.63	0.58	0.58	0.60	0.62	0.85	0.65	1.20
Total Responses	216	221	221	220	220	220	220	52

3. Here, the researcher wants to gain an overview of the effectiveness and economics of the property’s existing heating and cooking systems. In addition, information is sought about the need for apartment cooling during hot periods of the year. Space

heating refers to the heating system used to warm the air in a house or apartment. Water heating refers to the heating system used to provide hot water for washing. What fuel do you principally use for space heating and hot water in your home? (tick one box for space heating and one box for hot water heating).

#	Question	Gas	Electricity	Oil	Other	Don't know	Responses	Mean
1	Space heating	73	128	0	15	5	221	1.87
2	Water heating	74	126	0	13	8	221	1.89

Statistic	Space heating	Water heating
Min Value	1	1
Max Value	5	5
Mean	1.87	1.89
Variance	0.79	0.89
Standard Deviation	0.89	0.94
Total Responses	221	221

4. Considering your home space heating – do you feel that your space heating system:

#	Question	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	Don't know	Responses	Mean
1	Adequately provides for your heating needs?	31	136	26	17	4	5	219	2.28
2	Economically provides for your heating needs?	10	97	54	37	13	8	219	2.86

Statistic	Adequately provides for your heating needs?	Economically provides for your heating needs?
Min Value	1	1
Max Value	6	6
Mean	2.28	2.86
Variance	1.03	1.35
Standard Deviation	1.01	1.16
Total Responses	219	219

5. Considering the heating of water in your home – do you feel that your hot water system:

#	Question	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	Don't know	Responses	Mean
1	Adequately provides for your hot water needs?	43	142	18	9	3	0	215	2.01
2	Economically provides for your hot water needs?	10	103	55	32	7	8	215	2.75

Statistic	Adequately provides for your hot water needs?	Economically provides for your hot water needs?
Min Value	1	1
Max Value	5	6
Mean	2.01	2.75
Variance	0.58	1.22
Standard Deviation	0.76	1.11
Total Responses	215	215

6. Considering your home gas or electric cooker – do you feel that it:

#	Question	Strongly agree	Agree	Neither agree nor disagree	Disagree	Don't know	Responses	Mean
1	Adequately provides for your cooking needs?	33	147	25	10	0	215	2.06
2	Economically provides for your cooking needs?	12	119	54	22	8	215	2.51

Statistic	Adequately provides for your cooking needs?	Economically provides for your cooking needs?
Min Value	1	1
Max Value	4	5
Mean	2.06	2.51
Variance	0.45	0.79
Standard Deviation	0.67	0.89
Total Responses	215	215

7. Considering the cooling requirements of your home – do you feel that:

#	Question	Agree	Neither agree nor disagree	Disagree	Don't know	Responses	Mean
1	For more than three weeks in a year, the apartment feels hot enough to require air conditioning/cooling?	24	48	119	24	215	2.67
2	You would consider installing some type of air conditioning/air cooling in the future?	9	26	128	52	215	3.04

Statistic	For more than three weeks in a year, the apartment feels hot enough to require air conditioning/cooling?	You would consider installing some type of air conditioning/air cooling in the future?
Min Value	1	1
Max Value	4	4
Mean	2.67	3.04
Variance	0.67	0.53
Standard Deviation	0.82	0.73
Total Responses	215	215

8. This question looks at the weaknesses and strengths of the property’s existing heating, cooking and cooling systems and technologies from your perspective.What do you consider as currently being the positive and negative aspects of your current heating and cooking systems? (please write in the boxes provided). [responses removed]

Statistic	Value
Total Responses	174

9. This section looks at the householders experience or perceptions of an 'all electric' energy supply.Are you presently living or have you lived in a home that is heated by electricity only? (tick the appropriate box)

#	Answer		Response	%
1	Yes		130	62%
2	No		80	38%
	Total		210	100%

Statistic	Value
Min Value	1
Max Value	2
Mean	1.38
Variance	0.24
Standard Deviation	0.49
Total Responses	210

10. Do you think by having your apartment block and apartment supplied with electric only space heating, hot water provision and cooking rather than using other fuels that:

#	Question	Label 1	Count 1	Label 2	Count 2	Label 3	Count 3	Label 4	Count 4	Responses	Mean
1	Using electricity for heating, cooking and appliances would be more/less economical?	More	52	Less	77	Neither	54	Don't know	24	207	2.24
2	The generation of electricity from UK power stations to provide the power would produce more/less environmental pollution?	More	115	Less	24	Neither	35	Don't know	33	207	1.93
3	Indoor pollution from electric heating in an apartment would be more/less?	More	14	Less	132	Neither	35	Don't know	26	207	2.35
4	Using electricity only will provide the UK with a better/worse security of supply?	Better	97	Worse	27	Neither	53	Don't know	30	207	2.08
5	Using an electric cooker for all your cooking needs would be better/worse than using other fuels such as gas?	Better	46	Worse	54	Neither	91	Don't know	13	204	2.35
6	An electric only supplied apartment block would be somewhere you would personally want to avoid/want to live?	Want to avoid	35	Want to live	84	Neither	77	Don't know	11	207	2.31

Statistic	Using electricity for heating, cooking and appliances would be more/less economical?	The generation of electricity from UK power stations to provide the power would produce more/less environmental pollution?	Indoor pollution from electric heating in an apartment would be more/less?	Using electricity only will provide the UK with a better/worse security of supply?	Using an electric cooker for all your cooking needs would be better/worse than using other fuels such as gas?	An electric only supplied apartment block would be somewhere you would personally want to avoid/want to live?
Min Value	1	1	1	1	1	1
Max Value	4	4	4	4	4	4
Mean	2.24	1.93	2.35	2.08	2.35	2.31
Variance	0.92	1.36	0.62	1.30	0.81	0.66
Standard Deviation	0.96	1.17	0.79	1.14	0.90	0.81
Total Responses	207	207	207	207	204	207

11. This section considers key aspects of any future Modal Switching of energy supply and how acceptable this would be to householders. If your apartment block could be fuelled principally by electricity in the future - how acceptable or unacceptable do you think the following would be for your household and apartment? (tick one box only for each question below):

#	Question	Very unacceptable	Fairly unacceptable	Neutral	Fairly acceptable	Very acceptable	Don't know	Responses	Mean
1	Electricity for the apartment block is generated from small -scale wind, solar or Combined Heat and Power (CHP) plant installed on/in the building or in the neighbourhood	5	7	10	95	68	13	198	4.28
2	Undergoing additional construction work in the apartment to enable the installation of new heating systems in the floor or on the walls	32	74	38	33	17	4	198	2.70
3	Paying a higher price for electricity during peak times such as between 7:00am and 9:00am in the morning and 6:00pm and 8:00pm in the evening but adjusting your main usage to other times of the day when the cost could be much lower	13	24	46	86	19	10	198	3.53
4	Accepting the same level of pollution as currently experienced from electricity generation stations over the next 10 to 20 years but with substantial reductions in emissions later through the use of carbon capture and storage systems at power stations	10	14	54	74	28	18	198	3.76

Statistic	Electricity for the apartment block is generated from small - scale wind, solar or Combined Heat and Power (CHP) plant installed on/in the building or in the neighbourhood	Undergoing additional construction work in the apartment to enable the installation of new heating systems in the floor or on the walls	Paying a higher price for electricity during peak times such as between 7:00am and 9:00am in the morning and 6:00pm and 8:00pm in the evening but adjusting your main usage to other times of the day when the cost could be much lower	Accepting the same level of pollution as currently experienced from electricity generation stations over the next 10 to 20 years but with substantial reductions in emissions later through the use of carbon capture and storage systems at power stations
Min Value	1	1	1	1
Max Value	6	6	6	6
Mean	4.28	2.70	3.53	3.76
Variance	0.95	1.63	1.39	1.46
Standard Deviation	0.98	1.28	1.18	1.21
Total Responses	198	198	198	198

12. This section seeks to establish possible reasons for Modal Switching from the perspective of the householder. I have (or would) switch from gas to electricity because (please tick one box only for each question below):

#	Question	Agree	Neither Agree nor Disagree	Disagree	Don't know	Responses	Mean
1	Building developers are constructing apartments with only electric heating and cooking systems and no gas?	107	49	11	26	193	1.77
2	It is easier and cheaper to install electric heating than gas or other alternatives?	99	45	9	40	193	1.95
3	Gas in buildings can be more dangerous compared to electricity?	126	43	14	10	193	1.52
4	New stricter building regulations and legislation concerning energy use and carbon emissions can restrict the use of certain fuels?	77	58	5	53	193	2.18
5	Electricity has a wider range of domestic uses than gas?	139	36	7	11	193	1.43
6	Newer buildings are better insulated and therefore use less energy for space heating?	108	48	9	28	193	1.78

Statistic	Building developers are constructing apartments with only electric heating and cooking systems and no gas?	It is easier and cheaper to install electric heating than gas or other alternatives?	Gas in buildings can be more dangerous compared to electricity?	New stricter building regulations and legislation concerning energy use and carbon emissions can restrict the use of certain fuels?	Electricity has a wider range of domestic uses than gas?	Newer buildings are better insulated and therefore use less energy for space heating?
Min Value	1	1	1	1	1	1
Max Value	4	4	4	4	4	4
Mean	1.77	1.95	1.52	2.18	1.43	1.78
Variance	1.10	1.39	0.71	1.50	0.66	1.14
Standard Deviation	1.05	1.18	0.84	1.22	0.81	1.07
Total Responses	193	193	193	193	193	193

13. This section considers the importance of energy to householders compared to other household issues.Concerning your apartment and household - what issues do you consider are more important in terms of your expenditure and priorities than your current energy supply? (please identify two issues at most (other than mortgage, rent or food) and write in the boxes below): [responses removed]

Statistic	Value
Total Responses	148

14. This section looks at the acceptability of different energy sources and technologies. In the future, apartment blocks and flats could use various sources of energy and energy technologies. How acceptable to you would the following energy supply options for apartment blocks be? (please tick one box only for each option shown below):

#	Question	Very unacceptable	Fairly unacceptable	Neutral	Fairly acceptable	Very acceptable	Don't know	Not aware of the technology	Responses	Mean
1	Solar thermal panels on the apartment block roof to provide hot water	6	3	4	44	108	8	8	181	4.66
2	PV solar panels on the apartment block roof	6	2	2	48	103	9	10	180	4.71
3	Wind turbines on the building to provide electricity	8	11	8	54	80	10	9	180	4.41
4	Natural gas for heating from individual gas boilers	8	11	22	59	71	7	3	181	4.14
5	Biomass boilers placed in the apartment building and burning wood chips for heating	8	24	32	46	47	15	9	181	4.00
6	Energy from burning waste in controlled conditions	11	24	35	42	44	17	8	181	3.92
7	Heat pumps that capture heat from the ground or air	6	0	6	59	79	11	20	181	4.76
8	District heating fuelled by waste where hot water is supplied to the apartment block from a central system through pipes	9	4	6	45	94	11	12	181	4.61
9	Using different energy types (i.e. electricity, gas or district heating) at different times of the day when they may be cheaper to use	4	8	7	61	84	8	8	180	4.49
10	A centralised system fuelled by gas to provide apartments with hot water for heating and washing	10	4	11	52	86	9	9	181	4.45
11	An electric generator fuelled from natural gas, which provides electricity and heat for all apartments and is located in or nearby to the apartment block	9	10	15	59	70	9	9	181	4.29
12	Individual air conditioning units for cooling installed in each apartment	13	23	43	46	35	12	9	181	3.77

Statistic	Solar thermal panels on the apartment block roof to provide hot water	PV solar panels on the apartment block roof	Wind turbines on the building to provide electricity	Natural gas for heating from individual gas boilers	Biomass boilers placed in the apartment building and burning wood chips for heating	Energy from burning waste in controlled conditions	Heat pumps that capture heat from the ground or air	District heating fuelled by waste where hot water is supplied to the apartment block from a central system through pipes	Using different energy types (ie. electricity, gas or district heating) at different times of the day when they may be cheaper to use	A centralised system fuelled by gas to provide apartments with hot water for heating and washing	An electric generator fuelled from natural gas, which provides electricity and heat for all apartments and is located in or nearby to the apartment block	Individual air conditioning units for cooling installed in each apartment
Min Value	1	1	1	1	1	1	1	1	1	1	1	1
Max Value	7	7	7	7	7	7	7	7	7	7	7	7
Mean	4.66	4.71	4.41	4.14	4.00	3.92	4.76	4.61	4.49	4.45	4.29	3.77
Variance	1.12	1.14	1.65	1.45	2.16	2.29	1.44	1.56	1.22	1.57	1.71	2.26
Standard Deviation	1.06	1.07	1.28	1.20	1.47	1.51	1.20	1.25	1.11	1.25	1.31	1.50
Total Responses	181	180	180	181	181	181	181	181	180	181	181	181

15. This section considers the socio-economic implications of Modal Switching for city households. If you have an 'all electric' energy system or had an option to have it, to what extent do you consider each of the following aspects to be positive, negative or neutral? (select one box only for each question below):

#	Question	Positive	Neutral	Negative	Don't know	Responses	Mean
1	Having greater control over who supplies your electricity	141	31	1	5	178	1.27
2	Having short contracts with different electricity suppliers	104	51	8	15	178	1.63
3	Having greater independence by making use of electricity generated within the apartment block	128	33	3	13	177	1.44
4	Reducing electric consumption through the use of improved individual energy controls such as programmers, timers and smart meters	135	34	2	7	178	1.33
5	Reducing sources of energy pollution within your apartment through electric heating but consequently increasing pollution at electricity generating stations through the production of electricity	60	52	50	16	178	2.12

Statistic	Having greater control over who supplies your electricity	Having short contracts with different electricity suppliers	Having greater independence by making use of electricity generated within the apartment block	Reducing electric consumption through the use of improved individual energy controls such as programmers, timers and smart meters	Reducing sources of energy pollution within your apartment through electric heating but consequently increasing pollution at electricity generating stations through the production of electricity
Min Value	1	1	1	1	1
Max Value	4	4	4	4	4
Mean	1.27	1.63	1.44	1.33	2.12
Variance	0.38	0.83	0.73	0.48	0.97
Standard Deviation	0.62	0.91	0.85	0.69	0.98
Total Responses	178	178	177	178	178

16. This section looks at which organisations householders consider most appropriate to organise community energy supply schemes. Which one of the following groups or organisations would you trust to have responsibility for the supply and day to day management and maintenance of a community supplied energy system to the apartment block? (select one box only for each organisation):

#	Question	Most trusted	Least trusted	Neutral	Responses	Mean
1	Local authorities such as council	103	17	55	175	1.73
2	Electricity and gas utilities	24	79	72	175	2.27
3	Resident associations	40	49	88	177	2.27
4	Private energy management companies	10	84	82	176	2.41
5	Cooperatives	57	29	88	174	2.18
6	National government	60	37	78	175	2.10
7	Community energy supply groups	45	32	100	177	2.31
8	Other?	1	2	20	23	2.83

Min Value	1	1	1	1	1	1	1	1
Max Value	3	3	3	3	3	3	3	3
Mean	1.73	2.27	2.27	2.41	2.18	2.10	2.31	2.83
Variance	0.83	0.48	0.65	0.36	0.81	0.78	0.73	0.56
Standard Deviation	0.91	0.69	0.81	0.60	0.90	0.88	0.85	0.75
Total Responses	175	175	177	176	174	175	177	24

17. OK, you're past halfway now! This section looks at the basic layout of the householders apartment and the type of cooking and cooling technologies used. On what floor level is your apartment located? (ground, 1, 2 etc).

#	Answer		Response	%
1	Basement		1	1%
2	Ground		16	9%
3	1		23	13%
4	2		32	18%
5	3		39	22%
6	4		21	12%
7	5		13	7%
8	6		10	6%
9	7		10	6%
10	8		2	1%
11	9		4	2%
12	10		3	2%
13	11		0	0%
14	12		1	1%
15	13		0	0%
16	14		0	0%
17	15		2	1%
18	16		0	0%
19	17		0	0%
20	18		0	0%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	17
Mean	5.42
Variance	7.30
Standard Deviation	2.70
Total Responses	177

19. What type of floor layout does your property have?

#	Answer		Response	%
1	Completely open plan		3	2%
2	Combined kitchen and dining area		33	19%
3	Combined sitting room, dining and kitchen area		82	46%
4	Separate kitchen, dining and sitting room		55	31%
5	Other		4	2%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	5
Mean	3.14
Variance	0.64
Standard Deviation	0.80
Total Responses	177

20. How many walls of your apartment are exposed to the outside?

#	Answer		Response	%
1	One		54	31%
2	Two		99	57%
3	Three		18	10%
4	Four		2	1%
	Total		173	100%

Statistic	Value
Min Value	1
Max Value	4
Mean	1.82
Variance	0.43
Standard Deviation	0.66
Total Responses	173

21. What type of oven do you normally use for the majority of your cooking?

#	Answer		Response	%
1	Electric oven		142	80%
2	Gas oven		25	14%
3	Microwave oven		9	5%
4	Other		1	1%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	4
Mean	1.26
Variance	0.33
Standard Deviation	0.57
Total Responses	177

22. What type of hob do you use for cooking?

#	Answer		Response	%
1	Gas hob		52	29%
2	Electric hob		125	71%
3	Other		0	0%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	2
Mean	1.71
Variance	0.21
Standard Deviation	0.46
Total Responses	177

23. What type of air cooling/conditioning do you have in your apartment? (tick all boxes that are applicable):

#	Answer		Response	%
1	Air conditioning unit		1	1%
2	Natural cooling and ventilation		38	21%
3	Community cooling system		2	1%
4	Heat/cooling pump		2	1%
5	Ventilation fans		39	22%
6	Nothing		105	59%
7	Don't know		5	3%

Statistic	Value
Min Value	1
Max Value	7
Total Responses	177

24. This section considers householders energy consumption, fuel bills and any maintenance costs.What major electric appliances are used within your apartment? (tick all boxes that are applicable)

#	Answer		Response	%
1	Washing machine		124	70%
2	Drier		11	6%
3	Combined washing machine and drier		46	26%
4	Fridge/Freezer		172	97%
5	Freezer		19	11%
6	Portable electric heater		18	10%
7	Other (specify)		14	8%

Statistic	Value
Min Value	1
Max Value	7
Total Responses	177

25. What type of electric tariff are you currently using? (tick one box only)

#	Answer		Response	%
1	Standard		97	55%
2	Economy 7		40	23%
3	Economy 10		1	1%
4	Community tariff		1	1%
5	Other		2	1%
6	Don't know		36	20%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	6
Mean	2.32
Variance	3.85
Standard Deviation	1.96
Total Responses	177

26. Where is your electric meter located? (tick one box only)

#	Answer		Response	%
1	In the apartment		15	8%
2	On the wall outside		2	1%
3	On the common landing outside the apartment		15	8%
4	Elsewhere in the apartment block		86	49%
5	Don't know		57	32%
6	Not applicable		2	1%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	6
Mean	3.98
Variance	1.27
Standard Deviation	1.13
Total Responses	177

27. Where is your gas meter located? (tick one box only)

#	Answer		Response	%
1	In the apartment		8	5%
2	On the wall outside		6	3%
3	On the common landing outside the apartment		2	1%
4	Elsewhere in the apartment block		27	15%
5	Don't know		35	20%
6	Not applicable		99	56%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	6
Mean	5.10
Variance	1.79
Standard Deviation	1.34
Total Responses	177

28. Have any of the following items required repairs in the last two years? (tick all boxes applicable):

#	Answer		Response	%
1	Electric heaters		18	10%
2	Gas boiler		17	10%
3	Electronic controls - timers, programmers		20	11%
4	Water storage cylinders		7	4%
5	Immersion heater elements		13	7%
6	Electric/gas cooker or hob		13	7%
7	Air conditioning, cooling unit or system		1	1%
8	Air extractor system (over cooker or in toilet room)		17	10%
9	Radiator system including pipes, radiators, valves and pump		11	6%
10	Don't know		82	46%

Statistic	Value
Min Value	1
Max Value	10
Total Responses	177

29. How much do you estimate you spend on the following fuels over the last 12 months? (tick boxes for your fuel types)

#	Question	£10 - £500	£501 - £1000	Over £1000	Don't know	Responses	Mean
1	Electricity usage	76	60	9	5	150	1.62
2	Gas usage	28	15	1	15	59	2.05
3	Dual fuel usage	26	21	0	17	64	2.13
4	Heat usage (from a centralised type of hot water supply)	14	4	0	13	31	2.39

Statistic	Electricity usage	Gas usage	Dual fuel usage	Heat usage (from a centralised type of hot water supply)
Min Value	1	1	1	1
Max Value	4	4	4	4
Mean	1.62	2.05	2.13	2.39
Variance	0.56	1.53	1.48	2.05
Standard Deviation	0.75	1.24	1.21	1.43
Total Responses	150	59	64	31

30. Do you consider that the cost you pay altogether for electricity/gas/heat over a one year period is 10% or more of your household income?

#	Answer		Response	%
1	Yes		22	12%
2	No		112	63%
3	Other (Specify)		8	5%
4	Don't know		35	20%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	4
Mean	2.32
Variance	0.87
Standard Deviation	0.93
Total Responses	177

31. This section asks about the demographic details. This information will help the researchers find out if there are any differences in the answers by different groups of people. Your gender:

#	Answer		Response	%
1	Male		92	52%
2	Female		85	48%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	2
Mean	1.48
Variance	0.25
Standard Deviation	0.50
Total Responses	177

32. Your age group:

#	Answer		Response	%
1	16-24		21	12%
2	25-34		73	41%
3	35-44		29	16%
4	45-54		28	16%
5	55-64		25	14%
6	65+		1	1%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	6
Mean	2.81
Variance	1.63
Standard Deviation	1.28
Total Responses	177

33. How many people live in the property?

#	Answer		Response	%
1	One		49	28%
2	Two		101	57%
3	Three		16	9%
4	Four or more		11	6%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	4
Mean	1.94
Variance	0.62
Standard Deviation	0.78
Total Responses	177

34. Is your apartment owned or rented?

#	Answer		Response	%
1	Owner occupied		37	21%
2	Rented privately		78	44%
3	Rented from local authority		38	21%
4	Rented from housing association		22	12%
5	Other		2	1%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	5
Mean	2.29
Variance	0.94
Standard Deviation	0.97
Total Responses	177

35. How many years have you lived in this property?

#	Answer		Response	%
1	Less than 1 year		54	31%
2	1 to 2 years		69	39%
3	3 or more years		54	31%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	3
Mean	2.00
Variance	0.61
Standard Deviation	0.78
Total Responses	177

36. When do you primarily use your space heating?

#	Answer		Response	%
1	Mornings and evenings only		75	42%
2	All day		18	10%
3	Variable		84	47%
	Total		177	100%

Statistic	Value
Min Value	1
Max Value	3
Mean	2.05
Variance	0.90
Standard Deviation	0.95
Total Responses	177

37. What is the name of your apartment block and postcode? (enter name and postcode in the section below)

38. Would you be interested in taking part in a confidential interview with the researcher about Modal Switching and the implications of electric only energy supplies to apartment blocks and apartments?

39. Please fill in your details below so that we can contact you. These details will be stored in an encrypted, password protected database and then deleted once the research is complete. Only the researchers will have access to these details and they will not be passed on to anyone else for any other purpose. Not everyone who provides their details will be contacted for an interview.

40. You have now completed the research questionnaire. The research team would like to thank you for taking the time to help us with our work.

13.2 Stakeholders interviewed.

Name and organisation of stakeholder	Position	Contact details
Electricity Northwest Steve Johnson. Simon Brooke.	CEO. Low Carbon Projects Manager.	Electricity North West Limited Network Strategy Directorate 304 Bridgewater Place Birchwood Park Warrington Cheshire WA3 6XG. **steve.johnson@enwltd.co.uk** Tel: +44 (0)1925 534507 Mobile: +44 (0)7710 087 169. **simon.brooke@enwl.co.uk** Mobile: +44 (7785) 970903 Tele: +44 (1925) 846858.
National Grid Johnny Johnson.	Network Planning Manager, Network Strategy, Gas Distribution.	**johnny.johnston@uk.ngrid.com** Tel: (Int) 7153 6055 (Ext) +44 (0)1455 231055 Mob: +44 (0) 7836 290859.
Warm Front Erik Coates.	Operations Manager.	0191 247 3957 erik.coates@eaga.com
Switch2 Energy Solutions Ian Allan.	Director of IT Services.	The Waterfront, Salts Mill Road, Shipley, BD17 7EZ. **ian.allan@switch2.com** 08714236090, 07831782646 best number is: 01274532888
Dimplex, Creda, NOBO Andrew Bradwell.	Specifications Manager.	Millbrook House, Grange Drive, Hedge End, Southampton, Hants, SO30 2DF 07799863562.
Chatsworth Heating Products Nigel Constain.	Development Manager.	Unit 1, Brookside Avenue, Rustington, West Sussex. BN16 3LF 01276605808.
City South Manchester Housing Trust Tom Rock.	Head of Property Assurance.	Turing House, Archway 5, Hulme, Manchester M15 5RL, Tel: (0161) 227 1358, Fax:(0161) 227 1235, Mobile: 07775576062, tom.rock@citysouthmanchester.co.uk
Energy Saving Trust Manchester Steven Howles.	Energy Officer	Manchester City Council Town Hall Albert Square MANCHESTER M60 2LA 0800512012.
Salford City Council Sustainable Regeneration David Williams.	PFI Project Manager	Salford City Council, Phase 2, Swinton Civic Centre, Chorley Road, Swinton, Salford M27 5BW(0161 922 8797 mobile 07843 036 957 david.williams@salford.gov.uk
Wates Living Space Derek Cousins.	Site Manager.	Stretford House Chapel Lane, Stretford. M32 9AY. DD: 0161 865 4751 Fax:0161 865 6954 www.wates.co.uk
Salford Councillor. John Warmisham.	Lead Member for Adult Social Care & Health, Langworthy Ward.	0161 279 1972 [Councillor.Warmisham@salford.gov.uk]
Association for the Conservation of Energy Pedro Guertler	Research Manager	Westgate House 2a Prebend Street London

Darryl Croft		N1 8PT 020-73590863
BSRIA David Bleicher	Research manager/trainer	BSRIA Ltd Old Bracknell Lane West Bracknell Berkshire RG12 7AH 01344465589
Energy Networks Association David Smith	Chairman	6th Floor, Dean Bradley House 52 Horseferry Road London SW1P 2AF 020-77065107
Carbon Action Network (Durham Council) Andrew Stephenson	Chairman and Local Government Officer	2-4 Market Place South Leicester, LE1 5HB 0191-3833745
St Georges Island Residents Committee	Residents Committee Founder	Saint Georges Island, Manchester sgi@john-evans.net
Climate Energy Peter Chisnell	Consultant	Countrywide House Freebournes Road Witham Essex CM8 3UN 07515974554 01376531523
BEAMA and Electrical heating and ventilation association Kelly Butler	Representative	Westminster Tower, 3 Albert Embankment, London, SE1 7SL
North West Domestic Energy Alliance Brian Sexton	Representative	info@nwdea.org.uk
Community Energy Solutions David Lacey	Regional manager	Calls Wharf, 2 The Calls, Leeds, LS2 7JU Tel: 0113 237 2720
Centre for Sustainable Energy Ian Preston	Senior Analyst	3 St Peter's Court, Bedminster Parade Bristol BS3 4AQ 0117 934 1400

13.3 Key stakeholders questionnaire/topic guide – all stakeholder groups.

[Note: alteration in form of questions for various stakeholders – these are indicated by the relevant group colours - Government and Policy makers, Developers and Improvers, Utilities, and Manufacturers, where black font is used these are common questions for all groups]

Background information to the questions provided within the covering research letter.

Questionnaire and discussion guideline that will be used during the Provider interviews.

These questions are being asked to determine if a trend called modal switching exists or not. Modal switching in this context is when newly build or refurbished homes are supplied with electricity rather than natural gas to provide space / water heating and cooking. The questions also explore the reasons behind this change – if it is real – and any socio-economic implications that would be brought about by the change. The questions also explore stakeholder attitudes towards an all-electric future. The questions are typically grouped around the key themes: planning, main drivers and demand, regulations and construction, space heating and cooling, low carbon markets drivers and impacts, stakeholders and user feedback. Comments within the shaded boxes are for explanatory purposes only. Background information for the questions is provided within the covering letter that will be sent to possible participants.

1a) Providers Survey -

First, some of your perceptions about modal switching (why etc.):

Planning, main drivers and demand

1) Do you think that modal switching (change from gas to electricity) is happening?

2) Why do you think there is a trend toward *modal switching*, particularly in city centre housing?

3) What do you consider are the key drivers for modal switching in city centres?

First some of your thoughts about the technologies that you manufacture/sell:

Planning, main drivers and demand

4) Where do you provide electrical heating or cooling technologies to new homes, and in which building types?

5) Are there any particular electrical heating and cooling products that are in high demand? How do you think this will change in the future?

6) Are there any future technologies that you anticipate?

Next, how regulations and legislation are impacting modal switching:

Regulations and construction

7) Are there regulations or legislation that would impact on gas installations but could be encouraging electricity to be installed instead for heating in city households? Do you think this is likely to change in the future? If so why and how?

8) Do you think that an 'all electric' model could be successfully used for city housing (especially apartment blocks) in the future? If so why?

Space heating and cooling

9) What other changes do you envisage could happen in the future with respect to space/water heating, cooking and cooling in city housing?

I would like to look at the possible consequences of modal switching and any actions that are planned:

Consequences – 1 environmental. One consequence of using electricity in homes as opposed to gas is that a source of emissions (gas boiler and hob) is being removed, thus shifting an extra environmental burden to the power station which is often located in the countryside:

There will be some environmental consequences of using electricity in homes as opposed to gas, first and foremost being that a source of emissions (gas boiler and hob) are being removed, thus shifting an extra environmental burden to the power station which is often located in the countryside:

10) Do you think this is a good idea?

11) Was this a conscious decision?

12) Do you think the modal switching could be accelerated due to environmental concerns? If so, how?

Consequences – 2 energy. The additional electricity generation requirements of shifting between gas and electricity will place an added burden to the supply network:

13) Does any of your forward planning make allowances for this added burden? – How would this be carried out and over what time frames?

14) How do you think Government plans to reduce carbon emissions by 80% by 2050 will impact future city housing developments and retrofits?

Low carbon markets drivers and impacts

15) What are the main barriers to implementing low carbon solutions for city homes? How could these be realistically addressed?

16) Under current predictions for global warming - do you feel cooling requirements/demand for urban homes will change in the future?

17) What (policies and guidelines) are in place or in the pipeline to reduce fuel poverty for those living in city homes?

Stakeholders

18) Who are your stakeholders regarding future energy supplies to cities and city residential housing?

Feedback

19) Is there anything else that you want to say about the topic that I have not asked you? Is there anything else that you want to ask me?

14 Appendix 4: Heat-providing apartment block photographs

Figure 178 Christabel (background) and Sylvia (foreground) apartment blocks.

Figure 180 Roach Court apartment block.

Figure 179 Emmeline block before and after rehabilitation (Wilkinson, 2005).

Figure 181 Emmeline block after rehabilitation (Wilkinson, 2005).

Figure 182 Thomas Court apartment block (Wilkinson, 2005).

Figure 183 Friars Wharf apartment block.

Figure 184 CHIPs apartment block.

Figure 185 Northpoint apartment block.

Coley apartment block – not available.

15 Appendix 5: Manchester city apartment study

Manchester apartments list and heating types

Basic information source: UrbanLife Magazine (MEN Media) dated 15/06/11 **http://www.julietwist.co.uk/properties-to-buy-manchester**

	Apartment block name	Location	Apartment type	Built					
1	360	dandara castlefield	modern apartment blg			1			underfloor heating
2	109 Princess st		converted building		1				
3	144 Princess st	nr China town, Princess house??	modern apartment blg				1		
4	25 Church st	northern qrt	older city apartment blg		1				panel heaters
5	26 Princess st		older modernised city apartment blg		1				not clear?
6	27 Sackville st	near bus station	renovated flat in older property		1				
7	3 Towers	Collyhurst	renovated modern apartments				1		3 electric and 2 with centralised gas
8	38 High st	Smithfield, northern qtr	renovated older building		1				Electric panels
9	384 Chester rd	St Georges	renovated building		1				Electric panels
10	42/44 Sackville st		renovated building		1				Electric panels
11	48 Princess st		renovated building		1				Electric panels
12	79 Piccadilly				1				
13	Abito	Salford quays, Greengate	modern apartment building		1				not clear
14	Advent house				1				Electric panel
15	Albert mill	Salford university	renovated building		1				Electric heating
16	Albert park view	Salford	renovated apartment building			1			Central heating - gas.
17	Albion Mill	New Ancoats	new apartment building		1				Central heating - gas, electric???
18	Alboin works	Portland street	modern apartment building		1				Electric heating
19	Alexandra Mews	Alexandra road	Low level apartment block		1				Electric panels
20	Angel Meadows	Naples street	modern apartment building		1				Electric panel
21	Asia House		conversion		1				Electric panels
22	Aura Court	Percy st	new apartment block		1				Electric panels
23	Badby close	Ancoats			1				Electric panel
24	Barton Place	Green 1/4	new apartment building		1				Electric panels

25	Base	dandara castlefield	new apartment building		1				Electric panels
26	Bauhaus	Little John st			1				Electric heating
27	Beaumont Buildings	Mirabel st	renovated building		1				Electric panels
28	Beethan tower	Manchester					1		Wet system seen
29	Bevill Square				1				wet system
30	Bishops corner	Hulme	new apartment building		1				Electric panels
31	Boatmans				1				Electric panels
32	Brazil House				1				Electric panels
33	Bridgewater Bank	Bridgewater bank	new apartment building		1				Electric heating
34	Britannia Mill	Hulme road	renovated apartment building		1				Electric heaters
35	Britton House	Green quarter	modern apartment blg?		1				Electric panels
36	Broadway					1			
37	Brook House	Ellesmere st				1			wet heating system
38	BS41	City centre	new apartment building		1				Electric heating
39	Budding view	Northern 1/4	new apartment buildings				1		
40	Burton Buildings	former burtons menswear	renovated building				1		Ducted heating and air con
41	Burton Place	Castelfield	new apartment building		1				Electric panels
42	Cambridge House	Cambridge st	STUDENT ACCOM				1		
43	Caminda House	Stretford rd Hulme	new apartment building		1				Electric heating
44	Canel st lofts	gay village	renovated apartments as lofts			1			Wet system
45	Canterbury Gardens	Salford	low level newish apartment building			1			Gas heating
46	Casa urbano	Hulme high st			1				Electric heating
47	Casandra court	Salford Sainsbury's	older council type apartments			1			Wet heating system gas
48	Castle Quay	Chester road				1			wet system gas?
49	Castlefield Locks	castlefield locks	new apartment building		1				Electric panels
50	Castlegate	Chester road	new apartment building		1				Electric panels
51	Century buildings					1			Gas?
52	Chancery Gardens					1			wet system gas?
53	Chatsworth House	Lever st	semi modern block		1				Electric heating
54	Chepstow House	Chepstow st	renovated building		1				Electric storage heaters

55	Chimney pot park		appears to be houses			1			
56	China House	Harter st	renovated building		1				Electric panels
57	Chips	New islington	new apartment building				1		CHP system
58	Chorlton Mill					1			wet system
59	City Central					1			
60	City East	Hulme	modern apartment block		1				Electric panels
61	City Gate	Blantyre st	modern apartment block		1				Electric panel
62	City Gate 2	Blantyre st	modern apartment block		1				Electric heating
63	City Gate 3	Blantyre st	modern apartment block		1				Electric heating
64	City Heights	Victora bridge st	modern apartment block		1				Electric heating
65	City Lofts	Salfrod quays	Modern apartment building		1				Electric panel
66	City Point	Chapel st Salford	modern apartment building		1				Electric panel
67	City Point 2	Chapel st Salford	modern apartment building		1				Electric heating
68	City South	city road east	modern apartment building		1				Electric heating
69	Cotton Mill	samuel ogden st	renovated building		1				Electric heating
70	Dale st ***					1			
71	Damaz	sharp st	modern apartment building		1				Electric panel
72	Deansgate Quay	deansgate quay	modern apartment building		1				Electric heating
73	Delta point	Blackfriers			1				Electric panel
74	Design House	Northern quarter			1				Electric panels
75	Ducie Wharf		renovated building		1				Electric panels
76	East side Valley (Advent house?)	Eastside valley	modern apartment building		1				Electric heating
77	Eastbank	Gt Ancoats st			1				Electric heating
78	Egerton house	Saltra Salford			1				Electric heating
79	Express building	former express building	renovated building			1			Gas
80	Fairbairn building	Northern quarter			1				Electric panel
81	Fairbairn building				1				Electric panel
82	Falcon way - sportscity				1				Electric panel
83	Fire station square	Salford				1			not clear
84	Fresh	Chapel st Salford	modern apartment block		1				Electric heating

85	Freshfield (Charlestown)	4 miles north manchester!!!	looks like renovated tower block		1				Electric heating
86	Fusion	Salford	modern apartment blocks		1				Electric heating
87	Garden House	Northern 1/4	modern apartment block		1				Electric panels
88	Granby House	city centre	renovated apartment block		1				Electric panels
89	Granby village					1			
90	Great Northern Tower				1				Electric panels
91	Green croft	Higher Broughton			1				Electric panel
92	Green Quarter					1			
93	Gresham Mill	Salford	modern apartment block		1				heatstore' electric boiler and storage heaters
94	Grove Village	stockport road	modern lo level apartment building			1			wet heating system
95	Hacienda	whitworth st	modern apartment building		1				Electric panel heating
96	Hills Quays	knott mill Manchester	modern apartment building		1				Electric panel heating
97	Hilton tower						1		
98	Home 2	Chapeltown st	renovated apartment building		1				Electric heating
99	Hudson Building	great ancoats st	renovated building			1			?????
100	Hulton Square	salford quays	modern apartment buildings		1				Electric panels
101	Icon 25	northern 1/4	modern apartment buildings		1				Electric panels
102	Imperial Pt	Salford quays	modern apartment buildings				1		System not clear but covered rads
103	Islington Wharf	new islington	modern apartment building				1		Wet system - centralised system
104	J Brindley Basin	Pic village	modern low level		1				Electric panels
105	Jackson House					1			
106	Jacksons Wharf		modern apartment building			1			
107	Jefferson Place	Fernie st	modern apartment block		1				Electric panels
108	Jewel House	Thomas st	renovated house		1				Electric heaters
109	Junction House (works)	ducie st	renovated house		1				Electric panel
110	Jutland Wharf	part of paradise wharf	modern apartment building		1				Electric panel
111	Kingsley House	Newton st	renovated house			1			wet heating system
112	Lake House	Castelfeild	modern apartment building			1			not clear
113	Lamba Court	salford	modern apartment building		1				Electric panels
114	Lancaster 80	city centre			1				Electric panel

115	Lancaster House	Whitworth st	renovated building		1				Electric heating
116	Leftbank	Spinningfields					1		Air conditioning, wet system
117	Lexington 42	chorlton st	renovated building		1				Electric heating
118	Life buildings				1				Electric panels
119	Lighthouse	northern 1/4	modern apartment building			1			
120	Lincoln Place	Hulme street	renovated		1				Electric
121	Linen Quarter	denmark road	modern apartment building		1				Electric heating
122	Linx	Simpson st	modern apartment building		1				Electric panels
123	Loreto Place	Hulme	modern apartment building		1				Electric heating
124	Lowry Apartments	Fallowfield	new low level building			1			wet systems
125	Ludgate Hill	Citedel????	modern apartment building		1				Electric heating
126	Lumiere	City road east	modern apartment building		1				Electric panels
127	Lwr Eastside					1			
128	M1	????				1			
129	M3	Waterside development, Castlefield	modern apartment building		1				Electric panels
130	Macintosh Village (Mill)				1				Electric panels
131	Maddison Apartments (court)				1				Electric panels
132	Market buildings	Northern 1/4	renovated building		1				Electric heating
133	Masson Place	lord st	modern apartment building		1				Electric panels
134	McConnell building	Jersey street	renovated building			1			Wet system
135	Media city	Salford quays			1				Electric heating
136	Medlock place				1				Electric panel
137	Melia House	lord st	modern apartment building		1				Electric panels
138	Melrose apartments				1				Electric panel
139	Merchants Quay	Salford quays	modern apartment building			1			wet system
140	Mercury buildings	nr Piccadilly gardens			1				Electric panels
141	Millennium Tower	Salford quays	modern apartment building		1				Electric panels
142	Milners Wharf	New Islington	modern apartment block		1				Electric panels
143	MM2	ancoats	modern apartment building		1				Electric panels
144	Model lodging house	bloom st	renovated building			1			wet heating system - gas?

145	Moho	hulme	modern apartment building		1				Electric heating
146	Montana house	Princess street	Modern apartment building		1				Electric heating
147	Navigation house?	Piccadilly	modern apartment building		1				Electric panels
148	No1 Deansgate				1		1		Electric boiler and radiators
149	North Tower					1			
150	Northern Angel	Dyche street			1				Electric panels
151	NV buildings	Salford quays	modern apartment building				1		wet system - communal or gas??
152	Old Court house	Salford	Older renovated building			1			Wet system possibly gas?
153	Oldham street				1				Electric panel
154	Ophthalmic works				1				wet system
155	Oxford Place	Oxfrod Road	semi modern apartment building		1				Electric panels
156	Paradise Wharf		modern apartment buildings		1				Electric panels
157	Parkers Apartments	Corporation street	modern apartment building		1				Electric panels
158	Piccadilly Apartments	???				1			
159	Piccadilly Lofts	Dale street	Older renovated building		1				Electric panels
160	Pinhigh Place	Salford	modern apartment block			1			Gas central heating
161	Portland House	Portland street	Older renovated building		1				Electric panels
162	Portland Street	???				1			
163	Potato Wharf	Castlefield	Older renovated building		1				Electric panels
164	Premier Point	Barton st	modern apartment building		1				Electric panels
165	Princess house	Princess street	old/new apartment block?		1				Electric heating
166	Pulse	Stretford road	Large modern apartment block		1				Electric panels
167	Quadrangle	Oxford road area			1				Electric panels
168	Quay 5	Salford quays	modern apartment building		1				Electric panels
169	Quebec buildings	Bury street	modern apartment building		1				Electric panels
170	Radclyffe Mews	??????				1			
171	Redmires Court	Salford	modern apartment building?			1			Wet system
172	Regency court					1			Gas?
173	Regency House				1				Electric panels
174	Regents Park	salford	renovated			1			Gas heating

175	Richmond Court		Low level apartment block		1				Electric heating - E7
176	River City	City road east	modern apartment building		1	1			Electric panel
177	Riverdale Village	?????							
178	Rochdale house	Slate Wharf development	Modern apartment building??		1				Electric heating
179	Rosetti Place	City centre	modern apartment building		1				Electric panels
180	Royal Mills	Eastenr 1/4 Manchester	renovation and new build				1		CHP centralised district heating system
181	Royal Square	?????				1			
182	Sackville Place	Bombay street	older building		1				Electric panel
183	Sallys Yard	Hulme street				1			Gas central heating
184	Saltra ?	Salford Quays	modern shortened apartment block		1				Electric panel
185	Sarah Tower	not built???				1			
186	Skyline Central	Goulden steet	modern apartment block		1				Electric panels
187	Skyline Chambers	Ludgate hill	modern apartment block		1				Electric panels
188	Slate Wharf	several buildings here????	renovated building		1				Electric heater
189	Smithfield Buildings				1				Electric panels
190	Sorting House	Newton st	modern apartment block		1				Electric panels
191	Sovereign Point	Salford Quays	modern apartment block		1				Electric panels
192	Spectrum	Balckfreiers road			1				Electric panels
193	Sportcity Livings (the cube)	Near city stadium	modern apartment block - commonwealth games?			1			Wet heating system? Gas, common?
194	St Davids Court	chetham	new lower level housing			1			wet heating system
195	St Edmunds Ch	whalley range	renovated church		1				Electric heatstore
196	St Georges Ch		converted church			1			
197	St Georges Isl	Castlefield			1				All buildings electric panels
198	St James Park	????	Old council flats			1			
199	St Johns Gns	?????	Low level apartments			1			
200	St Lawrence Qy	Salford Quays	low level apartment block		1				Electric panels
201	Steel house	salford	modern apartment block		1				Electric heating
202	Stillwater drive	sports city area	modern apartment block		1				Electric heating
203	Stonebridge House	Coberg street	modern apartment block		1				Electric panels
204	Stretford road	Hulme			1				Electric panel

205	Tempas Twr		modern apartment blocks		1				Electric panels
206	Textile Apartments	Salford	restored old building		1				Electric panels
207	The 8th day	Oxford road area	modern apartment building			1			wet system - gas?
208	The Art House	George st	renovated building		1				Electric panel
209	The Bailey	New bailey street, Salford	new apartment block		1				not clear?????
210	The Bayley	Salford new bridge st	modern apartment building		1				Electric panels
211	The Birchin	Northern 1/4			1				Electric panels
212	The Boxworks	Urban splash boxworks	new apartment building				1		Hot water tank, underfloor heating
213	The Bradley				1				Electric panels
214	The Bridge				1				Electric panels
215	The Chambers	nr Albert sq	renovated building			1			wet system
216	The Citadel	northern 1/4	new apartment building		1				Electric heating
217	The Cube (sports city)					1			Wet system
218	The Dispensary					1			part of urban splash old building
219	The Drum	sportscity area	modern apartment building		1				Electric panels
220	The Edge	Salford??	modern apartment building		1				wet system but appears to be electric
221	The Foundry	lower chatham st	modern apartment block		1				Electric panels
222	The Frame	Openshaw	modern inside out block				1		communal type heating??
223	The Gallery	Off Deansgate			1				Electric panels
224	The Grand	Aytoun street	older building		1				Electric panels
225	The Green Building	Oxford road area					1		Centralised hot water and space heating with solar thermal and gas energy
226	The Hub		modern apartment block		1				Electric heating
227	The Lock	Whitworth st west	modern apartment building		1				Electric panels
228	The Met apartments	Northern 1/4	renovated building		1				Electric heating
229	The Mews	Eastbank, Gt Ancoats street			1				Electric panels
230	The Mill	???				1			Gas
231	The Nile				1				Electric panels
232	The Old Bank	Boundary lane	renovated building		1				Electric heating
233	The Red Buildings	City centre	modern apartment buildings		1				Electric panels
234	The Rope works	Little Peter street	modern apartment building			1			not clear but did see a radiator on one wall, vertical heater

235	The Royal	Salfrod Chapel st	renovated apartment building		1				Electric heating
236	The Vaults	Tariff street	converted old building		1				Electric panels
237	The Way					1			
238	The Wentwood	city centre	modern apartment block		1				Electric panels
239	The Works	withy grove near big wheel	modern apartment block		1				Electric panels
240	Tib Street	Northern 1/4	renovated building		1				Electric heating
241	Timber Wharf	Castelfield			1				Underfloor heating - possibly electric????
242	Tobacco Factory	Naples street	Renovated		1				Electric panels
243	Transport House	Crescent Salford	New build		1				Electric panels
244	Trinity Court				1				Electric panels
245	Trinity Gardens	????				1			
246	Trinity Riverside	Salfrod quays?	New build low level apartments		1				Electric panels
247	Turner street				1				wet system
248	Turner street	Northern 1/4				1			Wet heating system - Gas
249	Tuscany House		New build		1				Electric panels
250	Tutti Frutti	New Islington ???				1			
251	Vallea Ct	Green quarter	modern apartment block		1				Electric panels
252	Vancouver Quay	Salford quays	Lower rise new apartments		1				Electric panels
253	Vantage Quay		modern apartment building		1				Electric panels
254	Velvet House	Sackville street	converted old building		1				Electric panels
255	Venice Court		restored old building with new parts		1				Electric panels
256	Vibe	New broughton salford	modern apartment block		1				Electric panels
257	Vicus	Liverpool road	restored old building with new parts		1				Electric panels
258	Vulcan Mill	New Islington	modernised old working mill		1				Electric panels
259	W3	Whitworth street west			1				Electric panels
260	Wakefield House	New wakefiled street	conversion			1			Gas central heating
261	Walker House	Salford Quays	modern apartment block		1				Electric panels
262	Westpoint	near MOSI	modern apartment block			1			
263	Wharf close	Salford quays				1			Gas wet system
264	Whitworth Place					1			

265	Whitworth Wst	Off Oxford road	modern apartment block		1				Electric heating
266	Winnipeg Quay	Salford quays	traditional new build		1				Electric heating - possibly storage heaters
267	Woolham Place	Castlefield	traditional new build		1				Electric heating - possibly storage heaters
268	XQ7	near Quays	modern apartment block		1				Electric heating panels and heated mat
					Electric	**Gas**	**Combined**	**Not clear**	**Supporting details**
				Totals to date	**189**	**63**	**17**	**0**	
				Percentage (%)	**70%**	**23%**	**6%**	**0%**	
				Grand total	**269**				

16 Appendix 6: Data sources and collection for environmental and techno-economic study

Performance and technical data for the research were obtained from a number of sources including: LCA databases, manufacturers, the owners and residents of the buildings being studied as part of the case studies, energy suppliers and other stakeholders. Data and information for the case studies including heating technology types, materials used in the supply systems and the energy consumption have been obtained from:

Apartment development organisations and users

- the developers - UrbanSplash (http://www.urbansplash.co.uk/);
- the developers – FriarsWharf (http;//www.friarswharfapartments.co.uk);
- the energy company - Switch2 (http://www.switch2.com/);
- case study residents associations; and
- case study apartment block residents.

Manufacturers of heating technologies:

- Dimplex heating (http://www.dimplex.co.uk/);
- OSO hotwater (http://www.osohotwater.com/uk/);
- NOBO heating UK Ltd (http://www.noboheatinguk.com/);
- Andrews water heaters (http://www.andrewswaterheaters.co.uk/);
- Vaillant boilers (http://www.vaillant.co.uk/);
- Worcester Bosch (http://www.worcester-bosch.co.uk/);
- Potterton boilers (http://www.potterton.co.uk/index/);
- Itron (https://www.itron.com);
- Hamworthy Purewell Energy (http://www.hamworthy-heating.com/);
- Gledhill cylinders (http://www.gledhill.net/);
- Viessman CHP units and heat stations (http://www.viessmann.co.uk/); and
- Fernox water treatment (http://www.fernox.com/).

Technologies lifetime and replacement costs:

- taken from CIBSE design guides; (CIBSE, 2008; CIBSE, 2010b; Poyry et al., 2009) and selected manufacturers information.

Construction cost estimation and comparison:

- performed using current databases comprising of price and cost information along with cost guidance books including, (Hutchins, 2010a; Hutchins, 2010b; Spon's, 2010a; Spon's, 2010b; Spon's, 2012).

Input costs for gas and electricity:

- calculated from (DECC, 2010c) central scenarios and energy costs from energy suppliers tariff analysis.
- data for the electricity generation efficiency is taken from (OFGEM, 2010a).

LCA database and additional sources:

- the LCA database used is EcoInvent (v2.2) and this is used along with field collected data including - equipment used, material type and quantity, and energy demand. EcoInvent is a centralised, web-based LCA database developed and implemented by the Swiss Centre for Life Cycle Inventories (EcoInvent, 2010).
- data sources for the air monitoring and stakeholder studies are described in detail within Chapter 4 and Chapter 6 respectively.

Data collection:

For each of the case study buildings, the overall theoretical operational building and individual apartment energy demand has been calculated through the use of heat loss STELRAD software (Stelrad, 2010) and standard assessment procedures (SAP) software, SAP2005 (Energydesigntools, 2010). SAP estimates the annual energy demand and carbon emissions for a particular dwelling of specified dimensions and characteristics, taking into account heating and hot water system types, fuels, and heating controls. Standard guides have been used to check system conformity (CIBSE, 2010a; CIBSE, 2010c). Actual individual energy consumption data have been collected through the householder survey in each apartment block either as a cost or kWh per month and then used to determine an annual consumption. Where available, actual overall building energy demand data have been obtained from energy management companies to enable an overall comparison.

The heating systems installed in the apartment blocks have been surveyed and an inventory developed comprising of heating technologies, building internal energy supply systems and external energy supply networks. For the common building internal supply systems, the material types and quantities used are identified through direct system inspection, estimation and detailing. This includes: all pipe-work, valves, fittings, pumps, electric cabling, and insulation. Apartment block fabric construction information has been obtained from individual building and apartment inspections, available floor plans and discussions with building contractors and residents.

To enable a detailed sustainability assessment on electric and gas heating systems, data have been collected from case study buildings, the equipment manufacturers, stakeholders and an overall literature review. The material constituents of the technologies and systems are determined from manufacturer's literature and supplied details. However, where there were no detailed material descriptions or information, the type, proportion and quantity of the materials has been estimated based on experience and judgement. Wherever possible, the country of manufacture and transport routes have been sought from manufacturers.

17 Appendix 7: Twenty English cities with the largest populations

17.1 Largest twenty cities in England 2010 (ONS, 2011)

City	Population
London	7,200,000
Birmingham	1,074,300
Leeds	751,485
Sheffield	552,698
Bradford	522,452
Manchester	503,127
Liverpool	466,415
Bristol	428,234
Leicester	329,839
Wakefield	325,837
Coventry	316,960
Nottingham	305,680
Newcastle upon Tyne	280,177
Sunderland	275,506
Brighton	273,369
Hull	256,406
Plymouth	256,384
Wolverhampton	249,470
Stoke on Trent	249,008
Derby	248,752

18 Appendix 8: Indoor air quality monitoring – unit and process information

Figure 186 Air monitoring sensor unit front view.

[Photo shows on/off switch, data connection and power sockets].

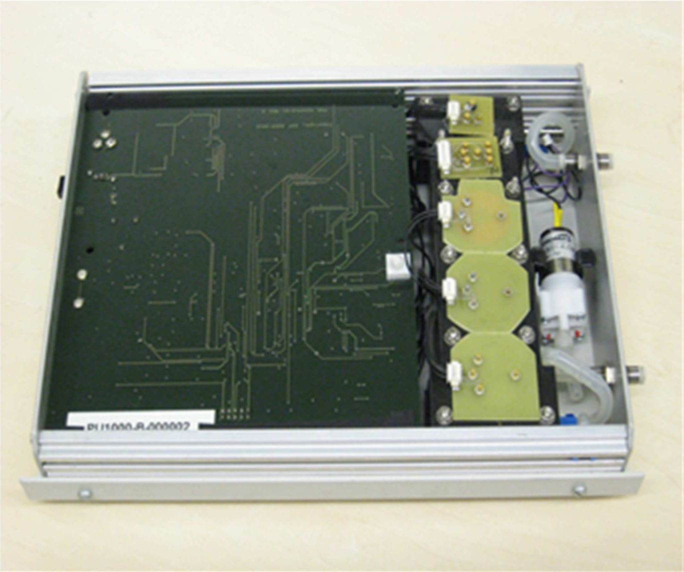


Figure 187 Air monitoring sensor unit open top view.

[Photo shows circuit board (left), sensor units (mid right) and pump (bottom right)].

Figure 188 Air monitoring sensor unit open top and front view.

[Approximate dimensions of unit – length 250 mm, width 180 mm and height 50 mm].

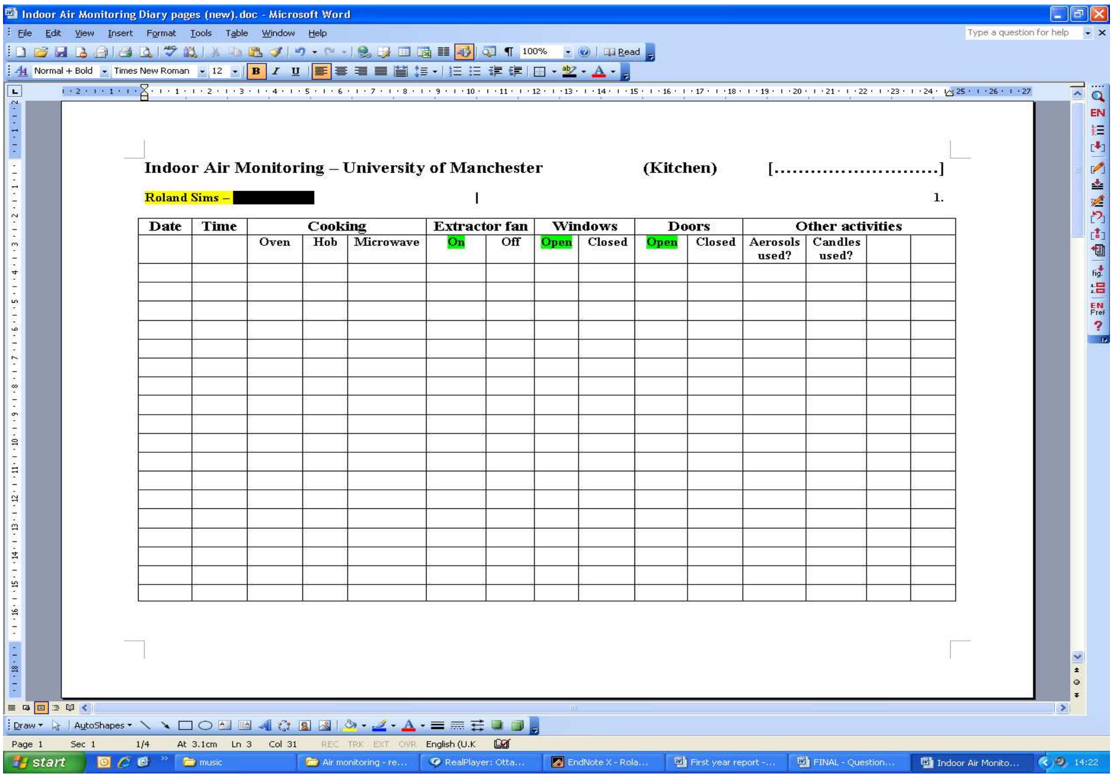
18.1 Air monitoring unit sensor technical details.

Sensor	Manufacturer	Range
Carbon monoxide (CO)	Alphasense	0 to 1000 ppm
Carbon dioxide (CO_2)	Alphasense	0 to 5000 ppm
Nitrogen dioxide (NO_2)	Alphasense	0 to 20 ppm
Sulphur dioxide (SO_2)	Alphasense	0 to 20 ppm
Volatile organic compounds (VOCs)	Alphasense	5 to 100 ppm
Relative humidity	Sensation	0 to 100% RH
Temperature	Sensation	-40^{o}C to 125^{o}C

18.2 Data collection methods and analysis techniques performed on the air quality monitoring

Activity	Data collection method	Analysis technique utilised
House layout	Drawings, photos and plans	Room volume calculated from dimensions
Air pollutant concentrations	Air monitoring sensor unit and internal memory card	Excel spread sheets – data calibration, time, concentration graphs and indoor/outdoor ratios Community analysis programmes – principal component analysis
Householder cooking, heating and related events	User diaries	Time related key events matched against sensor unit data i.e. (burning of toast or air freshener spraying etc.)

18.3 Occupants diary used during air quality monitoring in homes.



Indoor Air Monitoring – University of Manchester (Kitchen) [..........................]

Roland Sims – [redacted] 1.

Date	Time	Cooking			Extractor fan		Windows		Doors		Other activities			
		Oven	Hob	Microwave	On	Off	Open	Closed	Open	Closed	Aerosols used?	Candles used?		

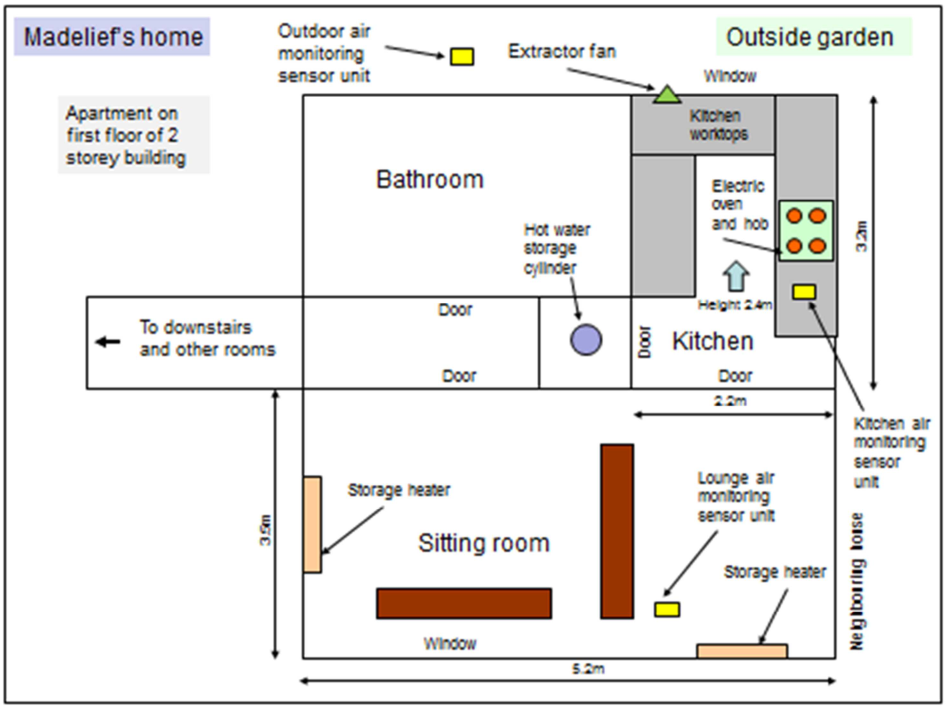


Figure 189 Plan of Madelief's kitchen and lounge including basic dimensions [not to scale].

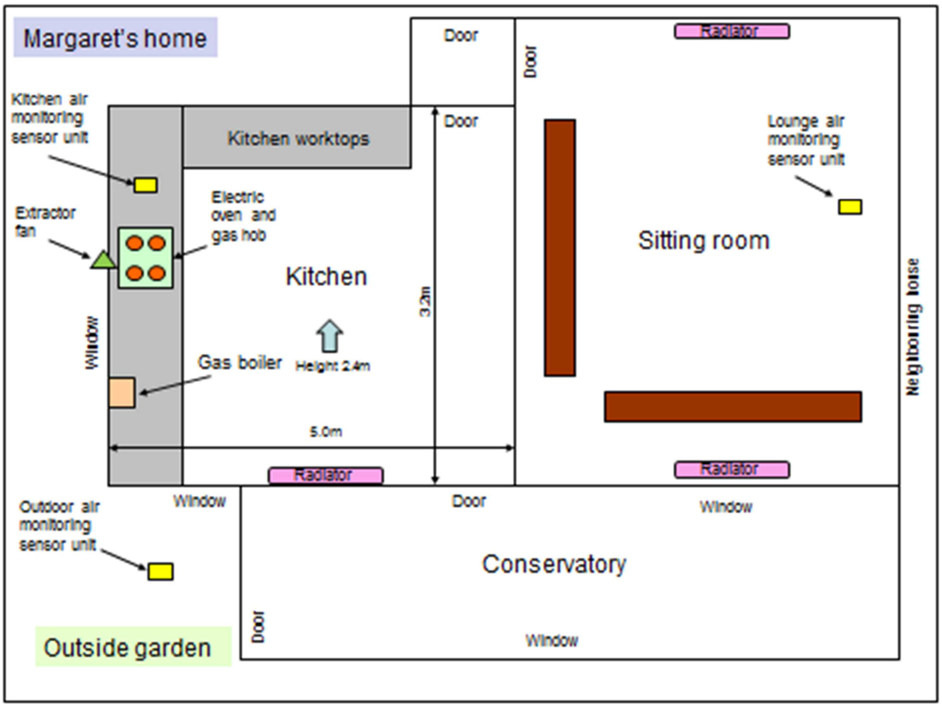


Figure 190 Plan of Margaret's kitchen and lounge including basic dimensions [not to scale].

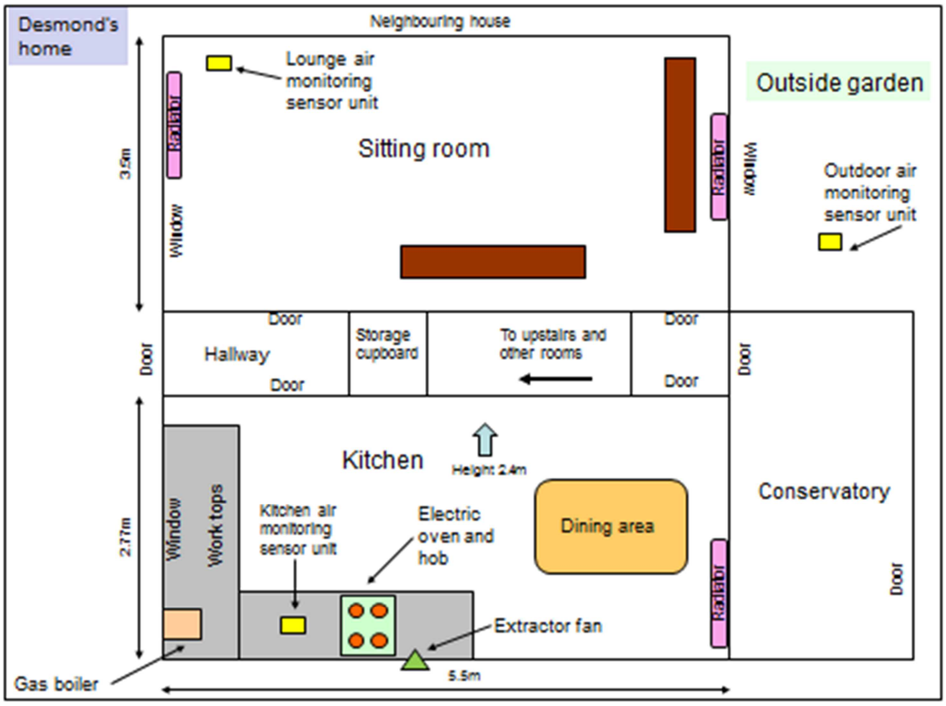


Figure 191 Plan of Desmond's kitchen and lounge including basic dimensions [not to scale].

18.4 PCA data summary for homes <u>inside and outside</u> emission during summer monitoring.

General statistics				
No. of Variables (rows)	4			
No. of Samples (cols)	2887 non zero of 3177			
No. of zero cells	113			
No. of non-zero cells	12595			
% zero cells	0.889204			
Maximum value	1			
Minimum value	-0.93385			
Range	1.93385			
Mean	0.235175			
Standard deviation	0.211904			
Median	0.232267			
Eigenvectors				
	1	2	3	4
[CO]/ ppm	0.207843	-0.780108	-0.460664	0.368811
[NO2]/ ppm	0.674661	0.0391681	0.590861	0.440661
[SO2]/ ppm	-0.638621	0.0842062	0.166899	0.74647
[CO2]/ ppm	0.306265	0.618714	-0.64095	0.335527
Results - variance				
	Eigenvalues	Cumulative Total	% of Total Variance	Cum. % of Total Variance
1	215.238	215.238	40.7093	40.7093
2	168.037	383.275	31.7819	72.4912
3	94.9366	478.212	17.956	90.4472
4	50.5074	528.719	9.55279	100

18.5 PCA data summary for homes <u>inside and outside</u> emission during winter monitoring

General statistics				
No. of Variables (rows)	4			
No. of Samples (cols)	3397 non zero of 3447			
No. of zero cells	76			
No. of non-zero cells	13712			
% zero cells	0.551204			
Maximum value	1			
Minimum value	-0.786241			
Range	1.78624			
Mean	0.249494			
Standard deviation	0.218259			
Median	0.231715			
Eigenvectors				
	1	2	3	4
[CO]/ ppm	0.322065	0.250702	-0.886732	-0.217091
[NO2]/ ppm	0.813325	-0.121048	0.125275	0.555118
[SO2]/ ppm	-0.480122	0.093073	-0.344276	0.801433
[CO2]/ ppm	0.0652704	0.955946	0.281933	0.0491966
Results - variance				
	Eigenvalues	Cumulative Total	% of Total Variance	Cum. % of Total Variance
1	217.014	217.014	39.2487	39.2487
2	166.886	383.9	30.1826	69.4313
3	121.138	505.038	21.9087	91.34
4	47.8828	552.921	8.65996	100

18.6 PCA data summary for homes inside emissions during summer and winter monitoring

General statistics	
No of variables	4
No of samples	5232 non zero of 5547
No of zero cells	149
No of non-zero cells	22039
% zero cells	0.671534
Maximum value	1
Minimum value	-0.7276
Range	1.7276
Mean	0.233609
SD	0.202733
Median	0.22581

Eigenvectors

	1	2	3	4
[SO2]/ ppm	0.427286	0.0386719	0.280854	0.858517
[NO2]/ ppm	-0.764671	-0.0666714	-0.3877	0.510413
[CO]/ ppm	-0.411444	0.634694	0.653051	-0.0374514
[CO2]/ ppm	0.251831	0.768911	-0.5868	0.0319928

Results - Variance

	Eigenvalues	Cumulative Total	% of Total Variance	Cum. % of Total Variance
1	329.484	329.484	40.6911	40.6911
2	212.747	542.231	26.2742	66.9652
3	185.962	728.193	22.9662	89.9314
4	81.5277	809.72	10.0686	100

Temperature and humidity

General statistics	
No. of Variables (rows)	2
No. of Samples (cols)	5547
No. of zero cells	0
No. of non-zero cells	11094
% zero cells	0
Maximum value	1
Minimum value	0.5927
Range	0.4073
Mean	0.846848
Standard deviation	0.0879382
Median	0.845946

	1	2
TEMP	0.873789	-0.486305
HUMID	0.486305	0.873789

18.7 PCA data summary for homes outside emission during summer and winter monitoring

General statistics				
No. of Variables (rows)	4			
No. of Samples (cols)	1052 non zero of 1077			
No. of zero cells	40			
No. of non-zero cells	4268			
% zero cells	0.928505			
Maximum value	1			
Minimum value	-0.93385			
Range	1.93385			
Mean	0.289071			
Standard deviation	0.266421			
Median	0.276596			
Eigenvectors				
	1	2	3	4
[CO]/ ppm	0.679421	0.577953	-0.11523	0.437126
[NO2]/ ppm	0.181179	-0.595884	-0.714915	0.317796
[SO2]/ ppm	-0.710653	0.387605	-0.271827	0.520427
[CO2]/ ppm	0.0231018	-0.400818	0.633821	0.661122
Results - Variance				
	Eigenvalues	Cumulative Total	% of Total Variance	Cum. % of Total Variance
1	77.1939	77.1939	42.0772	42.0772
2	66.3975	143.591	36.1922	78.2694
3	21.2363	164.828	11.5756	89.845
4	18.6301	183.458	10.155	100

19 Appendix 9: Stakeholder surveys

19.1 Pilot survey of occupants – questionnaire and summary results (in blue).

[Where numbers are shown – this relates to number of households, % related to the overall percentage of respondents].

Basics (Quantitative)

Name/Address **Gender**	**M / F.** 32/22 (59%/41%)					
Apartment type **Total number of floors in apt block**	Basic data Basic data	**What floor level is the apartment on?**		**Built (Apx yr)** Basic data		**Do you: Own** 12 (22%)/ **Let** 23 (43%)/ **Rent** 15 (28%)/ **Other** 4 (7%) **your property?**
N° of bedrooms	**1** 17 (31%)	**2** 31 (57%)		**3** 6 (11%)		**Other** (0%)
Type of occupants	**Single.**	**Family**		**Couple**		**Other**
Occupation						
Age range of primary occupants.	**18-24** 8 (15%)	**25-34** 21 (39%)	**35-44** 11 (20%)	**45-54** 8 (15%)	**55-64** 4 (7%)	**65+** 2 (4%)
Likely to move in the next 2-5 yrs?	**Yes –** 30 (56%)	**No –** 24 (44%)				
When is the property primarily occupied?	**At morning & evenings only** 35 (65%)	**All day** 6 (11%)		**Variable** 13 (24%)		**Comments:**

Heating types you have

Space heating type		**Water heating type**		**Cooling type**		**Cooking type**	
Individual gas boiler - 10		Electric Emersion heater - 14		Air conditioning - 0		Electric - 44	
Community hot water pipe - 0		Gas boiler heating - 10		Heat/cooling pump - 0		Gas - 10	
Electric heater panels - 39		Community hot water pipe - 30		Natural cooling and ventilation - 54		Other	
Number in apartment? Basic data		Direct / Indirect system					
Inter-		**Hot water availability** Basic data		Community cooling system - 0		**Building standard (per block): Insulation,** 3	

connected?						**High Glass Content, 3** **£Low, 2** **£Mid, 0** **£Upper 3**
Electric storage heaters - 5		Storage tank - 14		**Are there any renewable energy systems in place and working? None** **Ventilation fans? None**		
Number in apartment? Inter-connected? Timers? Basic data		Capacity/Height Basic data				
Electric towel rail. - 44		Instant hot water	-			
		Bath and/ or Shower	-			
Other electric appliances?						

Electric/Heat/Gas

Electric Tariff		**Heat Tariff**		**Gas Tariff**
Standard	**9**	Hot water only?	**30**	**10**
Economy 7	**5**	Space heating only?	-	
Economy 10	**0**	Both hot water and space heating	-	
Other/don't know	**0**			

Who operates and maintains the energy supply systems <u>in your apartment block</u>?

Utilities, ESCo, other

Who maintains the energy supply system <u>within your home</u>?

Landlord, Council, ESCo, Owner

Who do you pay for heat? – ESCo **How are Electricity / Gas / Heat metered in your home? –** Individual meters

Cost per month/year (elect)	**Cost per month/year (heat)**	**Cost per month/year (gas)**
£10-500 - 25	-	-
£501-1000 - -	**19**	**10**
£1000+ - -	-	-

Perceptions of existing and future heating and cooking systems

A) How much influence did the type of heating system have on you in selecting this property for buying or renting? **What other factors were more influential?**	None. Transport, location, close to friends, close to job.				
B) How well does your **space heating** provide for your heating needs? *(Heating level adequate, economical, and controllable?).*	**1** **Worst** **-**	**2** **5**	**3** **37**	**4** **12**	**5** **Best** **-**
C) How well does your **water heating** provide for your hot water needs? *(Heating level adequate, economical, and controllable?)*	**1** **Worst** **-**	**2** **7**	**3** **38**	**4** **9**	**5** **Best** **-**
D) What do you consider as being the **positive and negative** aspects of your current space and hot water heating?	Expensive to operate, less hot water available, good insulation in the apartment is helping reduce bills.				
E) What type of **space heating and/or hot water system** would you prefer? Why?	Gas.				
F) How important is the **cooling/air conditioning/ventilation** of your flat? Why?	Not applicable.				
G) What aspect of energy in your house would you change if you could? *Why?* *(Cooker, space heating, water heating, cool air provision, your provider?).*	Heaters, amount of hot water available.				
H) What renewable energy technologies do you think would be appropriate for the apartment block and your flat? **Why?**	Wind turbines, solar panels, solar hot water, district type heating.				
I) How do you **save money on your energy bills?**	Turn the heating off, turn heating down, go out, use oven only to heat room, zone the apartment.				
J) What is actually included in the supply and service costs for your energy supply – **can we see a bill?**	Basic data.				
K) What is your vision for future energy supplies in the UK?	Use of renewable energy, kinder to the environment.				

<u>Instant reaction questions</u>

L) Motivation for heating system type

Which of the following factors, if any, **would you personally like to see** from your current and future energy supply? **(Rank first three only).**

Cleaner and less pollution in the house	17 (10%)
Simpler and easier to use	12 (7%)
Supply always going to be available	15 (9%)
All or part uses renewable energy	29 (18%)
Better for the environment	25 (15%)
Saves on bills	54 (33%)
Operated and managed by the community	9 (6%)
Don't know / Other	1 (1%)

M) 'All Electric' Barriers

Which of the following factors **does or would most concern** you about living in an apartment where both the heating and hot water come from electricity? **(Rank first three only).**

Cost of future electric bills	54 (33%)
Poor temperature control of electric heaters and hot water	22 (14%)
Cost of maintenance	15 (9%)
Smart metering and network control	11 (7%)
Indoor pollution from electric heating	5 (3%)
Having to have an electric cooker	13 (8%)
Environmental pollution from power stations	35 (22%)
Don't know / Other	7 (4%)
Nothing	0 (0%)

N) Community supply

If your energy supply **is or could be turned over** completely to a community supplied system, **what factors would most concern you**? **(Rank first three only).**

Loss of individual control	54 (33%)
Don't trust companies to manage it properly	54 (33%)
Being locked into longer term contracts	18 (11%)
No individual boilers but sharing larger boiler with multiple properties	6 (4%)
Temperature of water supplied to apartment	9 (6%)
Maintenance of the system	5 (3%)
Electric cooking	13 (8%)
Don't know / Other	3 (2%)
Nothing	0 (0%)

19.2 Qualitative to quantitative conversion table

[Indicators and system values derived from online and stakeholder surveys]

1) This sheet shows the summary analysis to convert online questionnaire into data (values)

1 = best 6 = less good

		Unit	Panel	Storage	ASHP	Gas boiler	Combined gas and electric	District heating	CHP	Combined solar thermal + gas
	System effectiveness and efficiency									
Space heating adequacy			5	4	3	2	3	2	2	2
Water heating adequacy			4	4	4	2	4	2	2	4
Space heating efficiency			5	5	2	2	5	2	2	2
Water heating efficiency			5	3	3	2	5	2	2	2
Cooking adequacy										
Cooking efficiency			3	3	3	4	3	3	3	4
			22	**19**	**15**	**12**	**20**	**11**	**11**	**14**
	System perceptions and experience									
Electricity for heat provision - more economical?			4.5	4.5	4.5	2.5	3.5	2.5	2.5	2.5
Generation of electricity - more pollution?			4.5	4.5	4.5	2.5	3.5	2.5	2.5	2.5
Electric heating - more indoor pollution?			1.5	1.5	1.5	5.5	1.5	1.5	1.5	5.5
Using electricity only - more security of supply?			4.5	4.5	4.5	3	4	3	3	3
Electric only cooking - better?			4.5	4.5	4.5	2.5	4.5	4.5	4.5	2.5
Electric only home - somewhere want to live?			5	5	5	2	3.5	2	2	2
			25	**24.5**	**24.5**	**18**	**20.5**	**16**	**16**	**18**
	Acceptability of upstream factors									
Electricity generated in neighbourhood from CHP, solar or wind			5	5	5	5	5	5	2	2
Additional construction work to accommodate new heating system			3	3	5	4	3	4	4	4
Paying higher electricity price during peak periods but much lower at other times			4	4	4	2	4	2	2	2
Accepting pollution levels as of today but substantial reductions in next 10 to 20 years using CCS			4	4	4	3	3	3	3	3
			16	**16**	**18**	**14**	**15**	**14**	**11**	**11**
	Safety, regulations, and uses									
Building developers are constructing apartments with only electric heat			3	3	3	4	4	4	4	4
Easier and cheaper to install electricity than alternatives			3	3	3	4	3	4	4	4
Gas in buildings can be more dangerous			3	3	3	4	3	3	3	4
Strict building regulations and legislation can restrict the use of certain fuels			3	3	3	5	4	3	3	5
Electricity has wider range of domestic uses			3	3	3	4	3	4	4	4
Newer buildings are better insulated and use less energy										
			15	**15**	**15**	**21**	**17**	**18**	**18**	**21**
	Heat technologies and energy sources									
Solar thermal panels on apartment block			5	5	5	5	5	5	5	2
PV solar panels on apartment block										
Wind turbines on apartment block										
Individual gas boilers			3.5	3.5	3.5	4	3.5	3.5	3.5	3.5
Biomass boilers placed in apartment block			3	3	3	3	3	4	4	3
Energy from burning waste			2	2	2	2	2	4	4	2
Heat pumps			5	5	2	5	5	5	5	5
District heating			4	4	4	4	4	3	3	4
Using different energy types at different times			4.5	4.5	4.5	4.5	2.5	2.5	2.5	2.5
Centralised energy system			4	4	4	4	3	3	3	3
CHP energy system			4	4	4	4	4	4	3	4
			35	**35**	**32**	**35.5**	**32**	**34**	**33**	**29**
	Heat control and management									
Greater control over who supplies electricity			2	2	4	2	4	4	4	2
Short contracts with different suppliers			4	4	4	4	3	3	3	4
Greater independence using apartment block generated electricity			2.5	2.5	2.5	4.5	3.5	4.5	4.5	4.5
Reducing consumption through control, timers and smart meters										
Reducing pollution at apartment but increasing pollution at power stations			4.5	4.5	4.5	2.5	3.5	2.5	4.5	2.5
			13	**13**	**15**	**13**	**14**	**14**	**16**	**13**

		Panel	Storage	ASHP	Gas boiler	Combined gas and electric	District heating	CHP	Combined solar thermal + gas
System effectiveness and efficiency	Technical	22	19	15	12	20	11	11	14
System perceptions and experience	Social	25	24.5	24.5	18	20.5	16	16	18
Acceptability of upstream factors	Social	16	16	18	14	15	14	11	11
Safety, regulations and uses	Technical	15	15	15	21	17	18	18	21
Heat technologies and energy sources	Technical	35	35	32	35.5	32	34	33	29
Heat control and management	Technical	13	13	15	13	14	14	16	13

2) This sheet shows the analysis to convert grounded theory into data (values)

1 = best 6 = less good

Concepts	Categories	Indicator type	Panel	Storage	ASHP	Gas boiler	Combined gas and electric	District heating	CHP	Combined solar thermal + gas
Cost concerns not carbon concerns	Cost and profit significant		1	1	4	4	3	6	6	6
Profit significant player			1	1	3	3	4	5	5	3
Context of pricing			4	4	4	2	3	1	1	2
Value of future avoided energy not in policy			5	5	5	4	3	2	2	2
Excessive costs and focus on reducing costs			5	5	4	3	4	2	2	2
Spending on property for energy saving not priority			2	4	2	4	2	2	2	2
Long payback period issues			2	2	2	2	3	5	5	5
Build and leave mentality	Short term view prevails		4	4	3	3	3	2	2	2
Incentives important			1	1	3	1	3	4	4	3
Grant-less switching			5	5	3	5	4	2	2	2
Future pricing against time usage	Change through inducements		4	1	4	4	3	2	2	3
Lock-in for several years			5	5	5	5	5	6	6	5
Fuel poverty varies across country	Time value of energy and investments		5	4	3	3	3	2	2	3
Low incomes, benefits based occupants and poor tariffs			5	3	3	3	3	2	2	2
Better deals through cooperation			4	4	2	4	3	2	2	3
High costs of infrastructure development and renewal			1	1	3	3	3	4	5	3
			54	**50**	**53**	**53**	**52**	**49**	**50**	**48**
Gas first choice, clean, in love with gas, but safety heavy	Gas widely accepted and valued		4	4	4	1	2	2	2	1
Gas reserves and supply available, not demand priced			4	4	4	1	2	2	2	1
No material alternative to gas - no second dash for gas			3	3	3	5	4	3	3	4
Electric heat short term private sector market development thing			4	4	4	2	3	2	2	3
Gas systems oversized			1	1	1	3	2	4	4	3
Gas emissions improving, less significant in urban areas than transport			1	1	1	3	3	3	3	3
Ease and simplicity of installation			1	2	4	4	3	5	6	4
Move from individual gas to centralised gas	Centralised heat supply and local generation		4	4	2	4	2	1	1	2
Minimising losses through local generation, storage and use			4	4	4	4	2	1	1	2
Inefficient homes and electric don’t mix, smaller well insulated do	Home efficiency and electric heating issues		4	4	4	2	2	1	1	2
Electric future not only upstream generation	Electric available and adaptable		3	3	3	5	4	5	5	4
Electric always needed and can be fed from any appropriate source			2	2	2	4	3	4	4	4
Electric heat service small but electric volume through heat services										
			35	**36**	**36**	**38**	**32**	**33**	**34**	**33**
Regulations to kill off electricity	Regulations as an energy control mechanism		6	6	1	2	2	2	2	2
Manipulation of building regulations	Regulations as a bargaining tool		4	4	2	3	3	2	2	3
Renewables used as bargaining tool			4	4	4	4	4	2	3	2
Developers preferences			1	2	3	4	3	5	5	5
New routes to markets.			5	5	3	5	4	2	2	2
Future economics push towards electricity than gas	Large change		2	2	2	4	3	4	4	4
Change to involve a massive transformation but its speed unpredictable			4	4	3	2	2	2	2	2
Localised approaches to energy	Localised approaches to energy		5	5	5	5	4	2	2	3
			31	**32**	**23**	**29**	**25**	**21**	**22**	**23**
Importation requirements			2	2	2	5	4	3	3	4
Peak demand is major concern	Peak demand issues		5	5	5	3	4	2	2	2
Peak pricing, credits and mistiming			5	5	5	2	3	2	2	1
Changing of demand profile through demand flexibility, pricing and management			2	2	2	4	3	2	2	3
Fuels working together			5	5	5	5	2	2	2	2
Clustering effects and constraints	Clustering impacts		4	4	5	3	3	2	2	2
Dynamic network using real-time information and pro-active energy use management			3	1	3	4	3	4	4	3
Network savings through smart use			2	2	3	4	3	3	3	4
Heat storage at low demand times			4	2	3	5	3	2	2	2
Obligations of network operators	Network management, storage and control concerns		4	4	4	4	4	5	5	3
			34	**30**	**35**	**34**	**28**	**24**	**24**	**22**
Customer interaction and agreement to reduce network impacts	Interaction with consumer		5	5	4	5	4	3	3	3
Better understanding and information of system, savings and limitations			5	5	2	5	2	2	2	2
Sense of powerlessness and others agendas	Locally led network initiators		2	2	4	2	3	4	4	4
Faceless and exploitative private organisations and utilities			3	3	4	3	4	5	5	4
Network initiators			4	4	3	4	3	2	2	3
Locally led and supported initiatives			5	5	4	5	3	3	3	3
Exclusion from wider energy choices	Exclusion from choice		2	2	2	2	3	5	5	3
Poor quality of life and health issues from fuel poverty			5	5	3	4	4	2	2	3
Hassle factor, public perception and efficiency as key motivation issues			2	2	4	3	3	3	3	3
Improvements used as take back and higher temperatures			3	3	3	3	3	3	3	3
Not for always our problem	Ownership and motivation		3	3	3	3	3	3	3	3
			39	**39**	**36**	**39**	**35**	**35**	**35**	**34**
Insulation playing key role			4	4	4	2	3	2	2	2
Well planned, effective and efficient installed technologies.			3	3	3	2	3	2	2	4
Centralised systems rather than individual	[Duplicate]									
Heat and electric storage at local and individual levels			4	2	4	5	4	3	3	4
New technologies applied to system control and management	[Duplicate]									
Timeframes and time responsibilities with renewable technologies	Renewable timeframes and time responsibilities		2	2	4	2	2	5	5	5
Technologies changes promote switches	Technology switches and mutual fuelling		4	4	3	4	2	1	1	2
Duel fuel technologies and approaches	Bigger picture stuff		5	5	5	5	2	1	1	2
Clustering effects of social and inner city housing	[Duplicate]									
			22	**20**	**23**	**20**	**16**	**14**	**14**	**19**
Few carrots and sticks for low carbon measures	Few carrots and sticks from carbon measures		4	4	3	4	3	2	2	2
Less pollution but more concerns			4	4	4	3	2	4	4	2
			8	**8**	**7**	**7**	**5**	**6**	**6**	**4**

Original headings	Adjusted headings		Panel	Storage	ASHP	Gas boiler	Combined gas and electric	District heating	CHP	Combined solar thermal + gas
Cost	**Social acceptability**	Social	54	50	53	53	52	49	50	48
Heat	**Diversity of heat**	Technical	35	36	36	38	32	33	34	33
Regulations	**Development implications**	Social	31	32	23	29	25	21	22	23
Demand	**Demand implications**	Technical	34	30	35	34	28	24	24	22
Interaction	**Interaction and ownership**	Social	39	39	36	39	35	35	35	34
Technology	**Support to technologies**	Technical	22	20	23	20	16	14	14	19
Carbon	**Carbon measures and concerns**	Technical	8	8	7	7	5	6	6	4
	Fuel resilience	Technical	22	22	22	28	20	18	18	21
	Low income-high cost measure	Social	30	27	21	21	23	17	17	18

19.3 On-line questionnaire - participant information sheet

Participant Information Frequently Asked Questions (FAQ) Sheet

General Public and Organisations Opinions of *Modal Switching* in City Residential Energy Supply in the UK

Participant Information Sheet

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully. Please contact Roland Sims if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish you take part. Thank you for reading this.

Who is conducting the research?

My name is Roland Sims - I am a PhD student at The University of Manchester, supervised Professor Adisa Azapagic and Dr. Stephen Daniels.

Title of the research:

General public and organisations opinions of *modal switching* in city residential energy supply in the UK.

What is the aim of the research?

This research is exploring the reasons and trends in energy supplies to city residential housing. The main aim of the research is to find out what residents and organisations think about changes to city residential energy provision and the sustainable management of indoor pollution associated with energy use in buildings.

Why have I been chosen?

I would like to ask questions particularly of people who live in apartment blocks where there are common energy supplies (electricity, gas or heat) to each household.

What would I be asked to do if I took part?

Your involvement in the study would be to complete a short questionnaire that looks at:

- Your current heating, cooling and cooking system;
- The use of electricity for all households needs – heating, cooling and cooking;
- The implications of using alternative energy supplies and technologies; and
- Any social and economic implications of changes in city energy supply and its use.

The questionnaire takes about 20 minutes to complete. It is up to you to decide whether or not to take part but returning the questionnaire constitutes consent to taking part in the research.

If I decide to take part, what will happen next?

If you decide you want to take part in this study, please complete the online questionnaire by clicking here.

Should you require further information or assistance in completing the questionnaire - please contact Roland Sims, CEAS, The University of Manchester G5, The Mill, Sackville Street, Manchester, M13 9PL, 0161-306 4365 or roland.sims@postgrad.manchester.ac.uk.

What happens to the data collected?

It is anticipated that the findings of the study will be written up for publication in a scientific journal and presented at international conferences. The findings will also be shared with groups who work within the energy supply sector and it is hoped that these will contribute to developing a better understanding of any implications arising from a change of energy type to city homes. In addition, a summary report of the findings will be available from the research website www.sustainable-systems.org.uk once the study has finished.

How is confidentiality maintained?

All information that is collected about you during the course of the research will be kept strictly confidential. The only contact information required will be either a mobile telephone number or email address. Your name or any contact details will not be recorded on the questionnaire transcripts. Data will be stored and kept at Manchester University. All results will be anonymised and it will not be possible to identify individual participant's data.

Will I be paid for participating in the research?

The completion of the questionnaire is voluntary. To thank you for taking part in this research, you can choose to be entered into a prize draw. The prize is a single £50 Argos voucher.

Can you give me an introduction to what you want me to do?

We would like to ask you some questions about the way energy services such as gas and electricity are delivered to your home and how they are used for home heating, water heating, cooking and air conditioning or cooling. There are a lot of similarities in the way that these services are delivered and used and some important differences.

The change from using one energy type (gas, electricity, heat) to another is sometimes called different things - here we refer to it as "modal switching". Any change depends on local circumstances but could be particularly evident in cities. Sometimes, the change can be just for heating - at other times it can be for all uses. Systems can be easily designed into new apartment blocks and they can also be retrofitted into existing apartment blocks although that may mean extensive reconstruction work.

The objective of *modal switching* is to provide the majority of energy needed by households from electricity. This could offer several benefits to householders and communities, e.g.:

- Greater security of supply in terms of energy in the future;

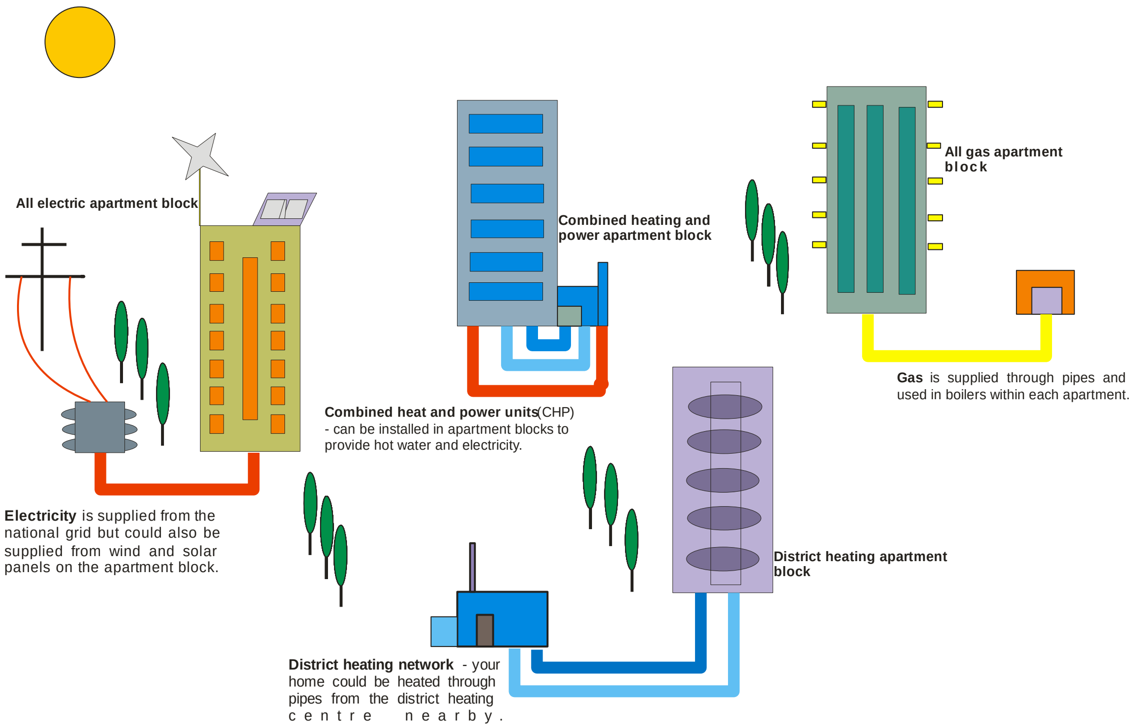
- Saving money overtime; and
- Using low carbon supplies from wind and solar and technologies such as heat pumps.

However, potential challenges to using more electricity could include:

- Carbon emissions from generating stations;
- Large unutilised heat losses from power stations;
- High peak power flows through the electricity network; and
- Cost.

Therefore, we would like to describe the systems and then ask you questions to see which aspects you consider to be strengths, which aspects you consider to be weaknesses, and whether – overall – you can see this "working for you".

The following diagram illustrates how an "all electric" and alternative energy systems would work.



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20 Appendix 10: Development of *grounded theory* for the electrification of heat

20.1 Emergence of categories from common themes in the data from organisation interviews

Key points (points regarded as important to the investigation)	**Codes**	**Guide theme**
Indicators for electrification of heat: Electricity more expensive than gas Occupants only switch if cost effective Electrification of heat (gas to electricity) needs sizable incentives Customers could be persuaded to switch through technology changes but would require national scale conversion Current extent of heat electrification through installation of heat pumps unclear Modern form of electric heating already installed through social assistance programmes House developers install the cheapest heating systems Passive house continues to need electricity for heat recovery and heat pumps Mains gas is first choice fuel for occupants because it is cheapest. The renewable heat incentive is established to start delivering on heat by electricity Trend seen in inner city properties where more electricity is being used – both storage heaters and panel type heaters and some ASHP - most properties are flats and apartments When considering electricity volume - the only way is by looking at the heating services and take volume away from the likes of gas, oil etc. Heat service penetration is only 5-6% but if that is 20-25% that could be very substantial for the industry Disagree that there is a change from gas to electricity but a change from individual gas to centralised forms of gas sourced heat supply to apartments Upstream generation is not the only solution to an electric future – reforms, infrastructure development strategy, and smart meter rollout are important to support an energy shift.	Cost Cost effectiveness Switch through technology changes Technology progress unclear Support within social housing Electricity always needed Gas first choice Incentives important Inner city trend Electric volume through heat services Electric heat service penetration small More individual gas to centralised gas Upstream and downstream electric focus needed.	Planning main drivers and demand
Reasons for electrification of heat:		

Government plans for the electrification of heating Driven by short term ‘cost concerns’ rather than ‘carbon concerns’ Observed switch from gas to electricity in cities during last five to eight years Landlords taken out gas and gas systems from apartment blocks and replaced with electric heating Emphasis by landlord and occupants on reducing maintenance or the need for gas safety certificates Proliferation of smaller housing units with improved insulation and reduced energy needs but using electricity Electric heating, especially electric panels used to supplement space heating in efficient homes Electric only systems help to avoid a whole raft of infrastructure within dwelling units Current regulations reflect a major disincentive for conventional electric heating but they are positive toward electric heat pumps Council properties create clustering effects resulting in large areas with mono-energy systems Trend seen more in the private sector where developers are trying to reduce their capital expenditure There is a tri-lemma: security of energy supply, progress toward low carbon economy, and energy price affordability Trying to change the demand profile – the storage of heat or electricity in any system will now be important.	Government plans Cost concerns not carbon concerns Recent short term switch to electric heat Reducing costs Smaller housing units and improved insulation Electric supplementing space heating Reduction in infrastructure requirements Clustering effects of mono-systems Private sector initiative Recognition of di and tri-lemmas Demand profile changes.	
Drivers for electrification of heat: New build market in England worth 80 to 90% electric panels in terms of heating for apartments Older buildings retrofits especially on the social housing side tend towards storage heaters Planning requirements and renewable energy targets within SPDs and LDFs, have an effect on type of heating systems installed Building regulations dissuade developers from using electricity for heating due to cost and emission reasons. Largest driver for the electricity supplier: environment, costs, no…something else …. its profit really, with debts to service these must be dealt with through raising electric tariffs or raising volume of sales Guaranteed revenue stream Electric heating is probably always going to be the cheapest capital cost, it's always going to be the highest running cost, until it comes a time in decades ahead and have a lot more renewables on the grid Not allowed to tell bidders what to do…. they are given the specifications and costs that they have got to stay within - how they actually provide the solution is up to them.	 New build significant for electric heating Retrofits easier for electric Tight requirements limit electric Profit significant player Cheapest capital, highest running cost Renewables to green future electricity.	

Technology locations: Import content (CO_2) from the UK network is about 0.6 kg per kWh because of the use of coal in the UK…the addition of offshore wind takes it below the 400g per kWh mark Likely that a significant increase in electric heat will add complexity to the electricity network because the location on the system of generating plant and the nature of the consumer load is likely to alter significantly.	Variable generation locations.	
Regulations and legislation: With current building regulations, difficult to get all electric systems accepted unless some kind of renewable energy is also installed Changes and amendments to the building regulations are expected to occur during 2013, 2016, 2019 Difficult and more demanding to run gas to every single flat hence the move towards centralised type gas plants No specific safety implications with going up particular heights and using gas systems but they must be ventilated and accessible Subtle manipulation of building regulations can occur in favour of electricity SAP operates within a short-term policy time frame, and is not mindful of the longer- term strategic view of a better-balanced energy supply. The reason why solar was there was to comply with the local authority requirement for 10% renewable energy on new buildings - the developer had to do it or do something anyway so the cost of it was kind of spread across the cost of the building.	Renewables used for bargaining Tightening of regulations Gas infrastructure and safety heavy Manipulation of building regulations.	Regulation, legislation and construction
Success of electrification of heat: To be successful in electrification of heat would necessitate a transformation of the likes rarely seen since industrialisation Success would need to be in the context of electricity pricing If these technologies are going into in-efficient homes and the price of electricity is expensive then we can have chaos It was a market development thing – now depends on the scale of cheaper electricity Generic switch anyway to electricity from gas and decentralised electricity is one of the ways forward About public perceptions and how the technology moves on…. if for example new space heaters are more efficient	Massive transformation Context of pricing Inefficient homes and electric don't mix Was market development thing Decentralised electricity and electric heat Public perception and efficiency Proactive energy use management.	

Home area networks (HAN) in new buildings allow domestic consumers to proactively manage their energy use resulting in greater control and reduction of energy consumption in UK households.		
Future changes to heat: Successful district heating schemes where led by local authorities rather than central government where they have local knowledge and/or ownership of many buildings Potential now to make the building so thermally efficient that you don't need heating in the building but water will always be required in some shape or form - solar hot water could help to reduce demand on the traditional sources SAP works against electricity particularly and therefore electric is good for refurbishment only The 'holy grail' for integrating components would be: a centralised system with a buffer tank to smooth the cycling of the heat pump, the solar thermal panels output and a log burner would be sensible to provide lifetime returns on investments Two alternatives may exist to accommodate electric heat – over capacity of generation in order to maintain the supply or …consumers will be required to be more flexible regarding their electricity use. Electric heating as a system can be fed from any kind of renewable source and renewable source of electricity!! Driven by developers and about them trying to make the ease of installation a lot simpler for themselves …and for their….. customers Smart metering and network approach is the right approach to take – it feels the right thing to do – it going to be the cheapest way customers will get the service that they require and we take a more critical role in helping them interact with us It is felt by some developers and local authorities that it would be more cost-effective to install larger CHP/heating schemes to serve a number of buildings than to go for individual units Whilst central boilers are inherently more efficient than individual boilers the overriding reason for centralised scheme is the ability to convert at an appropriate point in the future to a more sustainable fuel source The cost to implement other heating solutions in things which are already built - particularly in urban areas is going to be a real challenge and particularly around delivering heat in peak times for [really low periods] of time of the year either you need to do something … if you undergo electrification… you have to find some local electric storage that allows you to do that ……otherwise this would just be astronomical with very little utilisation	Local authority led Less focus on space heating more on water heating SAP works against electricity Heat storage required Centralised systems Over capacity or consumer demand flexibility Electric fed from any renewable source Ease of installation Interaction of players New technologies for system and demand management Centralised systems rather than individual Future easy conversion Localised electricity storage Duel fuel technologies.	Heat providing systems

Duel fuel micro CHP systems have the ability to use gas but also to generate electricity on a dual fuel system.		
Gas heat: Gas systems are often oversized because boilers and their associated systems only come in certain sizes Duel fuel systems have the ability to utilise gas but also generate electricity and offer the potential to save money, through their ability to export power Emissions from gas heating and cooking can be a problem especially if the house is well sealed with high insulation levels Gas will move towards main electricity generation and CHP units rather than be used individually in occupants' houses. [Covered in previous section as well at occupants level] Communal gas systems do not require landlords gas certificates and annual boiler maintenance costs.	Gas systems oversized Gas microchip flexible Possible higher indoor emissions Centralised gas rather than individual Requirement for certificates and annual maintenance High cost of gas pipe installation.	
Electric heat: Within SAP gas is seen as clean and electricity as dirty Electric systems have space heating units that are sized exactly to meet the heat output The sale of the electrical panels has declined since the standards of SAP have increased SAP works against electricity particularly and therefore, electric systems are good for refurbishment only SAP changes in 2013 should kill off electric heating completely Future electric systems will take advantage of being fed from any kind of renewable source of electricity Current market and policy barriers prevent the wider production of heat from low carbon electricity Cost of installing electric supply and the associated transformers is prohibitive Controls for electric systems very important and include: timers, thermostats, and sophisticated controllers Tenants require training and briefing to enable them to understand fully the heating system – without this, it is not operated effectively or economically Improved insulated hot water cylinders hold their heat very effectively. [Covered in previous section as well at occupants level] A lot of the carbon costs will effectively determine which fuels are going to used Off-peak cheaper electricity has an advantage and helps change people's behaviour through pricing signals – system recharging can now be conducted remotely.	Gas clean, electric dirty Electric system sized exactly Declining sales of resistance equipment Regulation to kill of electricity Flexible in generation source High cost of transformers and switchgear Electric controls support control and management Hot water storage effective Carbon cost determine fuel type used Off peak cheaper electricity important.	

High demand technologies: Correctly installed heat pumps PV panels Solar thermal Private wire decentralised electricity networks from decentralised energy scheme (DES) Heat recovery products.	Well planned, effective and efficient installed technologies.	
Costs installation: Electric generally has a simpler and easier installation and lower cost Improving materials and manufacturing processes means they are relatively cheaper than 20 years ago however, excavation and reinstatement is much more expensive Once a system is installed – the customer is usually locked in for 10 to 15 years 80% of it is achieved by doing the core … improved heating systems and proper insulation Cost of installing the supply and transformers has been prohibitive especially in Manchester First is you need a large plant room and where you can sell a cupboard in London for 150,000 pounds … that's a lot of revenue gone.	Simpler and easier Material and manufacturing improvements Lock-in Good insulation Limiting space for plant.	
Costs operational: Household is classified as being fuel poor if a fuel bill in excess of 10% of income is required to maintain adequate domestic thermal comfort in winter Costs of carbon being passed directly onto customers in some way, shape or form and therefore their use of the fuel source for heating will become quite important There are economy 7, 10 etc. customers at the moment – they will change because we will have clusters of customers that we need to manage within the local context in a more dynamic manner There's always going to be an interaction between electricity and gas costs Finding is that they had been paying on peak costs when they should have been paying on off peak costs If we could align with an energy company so that we will offer our residents a better deal for duel fuel and for electric Main thing is to get the properties more efficient recognising electricity prices are going to go up Offset any future heating cost rises - so by having a 20% reduction in actual usage you still get the cost of fuel going up proportionally but effectively save or break even Private energy managing companies have different types of contract – where they take the full risk on	Excessive cost Carbon costs Future pricing against time usage Interaction Ensuring correct tariff Better deals through cooperation Ensuring home efficiency Utilising incentives Private management.	

organising the supply, managing the system and billing, or just meter reading and billing. Solar thermal would qualify for RHI phase one.		
Existing technologies: Electric panel heaters Electric storage heaters Individual gas boilers – condensing, modulating or basic Immersion heaters Foam insulated water storage cylinders Gas or electric cooking by oven or hobs - induction and halogen hobs along with standard electric plate type.		
Future technologies: ***District heating:*** City councils are keen for heat networks to be developed but require network initiators Successful schemes have been led by local authorities rather than central government Easier to install district type heating on new developments giving little disruption Community heating networks are generally rated very positively – most notably through security of supply and taking the responsibility for purchasing and maintaining equipment from occupants Community heat has benefit of not having to store costly domestic hot water within each individual dwelling Concerns in having to have an electric cooking when using district heating District heating works well if the community are behind it however developers tend to deal with their own issues rather than being part of any collective action. ***Micro-generation and renewables***: Developers prefer solar water heating, PV and ASHPs as the building design is not affected and they are relatively easy to install Housing associations prefer low cost, low maintenance technology options Limited interest in micro-wind due to reliability, maintenance problems and wind profiles in urban areas PV has proved popular through FIT's.	Network imitators Led locally by communities Reduced storage needs Cooking concerns Developers preferences Low cost, low maintenance.	
Alternative energy supplies Stakeholders are keen to ensure that upstream generation is not the only solution to an electric future. There is also no material alternative to gas for heating - biogas is great from AD but limited to around 10% of	Electric future not only upstream generation No material alternative to gas	Emission shifting

customer domestic demand. What the speed of change of electricity we don't know, we are unsure but we can see the longer term move to … if we go to nuclear and large offshore wind then the carbon content will be a lot less than what we have in gas …and the economies will push us more towards electricity than gas ……but what the speed of changes is difficult to predict at the moment There is also a little bit of divergence here because we are also seeing….. on those roofs that face south and get a little bit of sunshine ....they are putting in storage tanks and PV and just using gas to top it up The Government remains in love with gas, but the future is clearly a sensible generation mix, which will include gas and a significant contribution from 'clean' electric.	Future economics push towards electricity than gas Speed of change unpredictable Buildings adapting to new technologies In love with gas.	
Environmental concerns Preference is given to burning fuels at the place of use rather than a long distance away because of energy efficiencies in terms of transmission losses Natural gas is perceived as a fairly clean burning fuel Changes to the fuel used for transport and transport modes have much bigger and more noticeable impacts on urban air quality in cities Consideration given to the big infrastructure requirements of the country rather than the individual requirements.	Localised combustion to minimise losses Clean fuel City transport emissions comparatively significant.	
Emissions: Current electricity generation is very much north to south Tendency to forget about local emissions with electricity as this is often in remote parts of the country where the fossil fuels are located Gas likely to be used for main power generation and CHP plants With small and medium-sized electricity plants a dilemma exists, where there's much less pollution from previously, but more concerns than previously. Modern technology and boilers and so on and so forth … means that emissions and the amount that comes out is very small if it is done correctly …certainly with air quality parameters and that .. So in that way, if it is correct … you help them improve air quality overall. .. but it doesn't always work in that manner The CCC calculations suggest that the current average emissions from the power sector, around 500 g CO_2 per kWh, need to be reduced by a factor of then to 50 g CO_2 per kWh by 2030..... but there should be no second	North to south supply Local emissions forgotten Gas used for generation Less pollution but more concerns Improving boiler emissions No second dash for gas.	

dash for gas.		
Energy security: Uncertainty over potential reserves and political issues may limit the impact of shale gas. More dramatic than shale will be the global impact of recently found conventional gas reserves.....mostly offshore and will require LNG projects to make them viable Where is the next generation going to come from …that could mean changing the business model… there could be third parties coming in and providing electricity from offshore … onshore wind farms …and then use gas fired stations as a balancing mechanism …and then provide a route to market through various systems.	Shale gas reserves LNG availability Business model change New routes to markets.	
Renewables: Now over 10% of all electricity generated is coming from renewables ....wind is the dominant renewable technology, generating 45% of the UK's clean energy.	Renewable contribution increasing.	
Scenarios: Real crystal balling Based on the original home improvement scenario developed by the council.	Crystal balling Local scenarios.	
Network performance Electric network supply experiencing clustering constraints and issues with start-up currents Existing electricity networks not designed to cope with what is foreseen for future electric heating Obligations on network operators to 'build and operate an efficient and economic distribution network' Two possible electricity network approaches exist to deal with the electrification demands: redesign and rebuild the networks to cope with the additional demand adding assets, and more carbon content. Alternatively, improve interaction with customers so that they will have the requirements that they want but at the same time, minimise possible impacts on networks Networks will become more dynamic with flows back and forth with greater inter-activity and interaction between network operators and the final customer. 0.57% throughput is the amount of leakage at the moment – remarkably little compared to electricity losses or water losses If we are able to look at the transmission network, you know losses have reduced, because we are not moving the energy in the same lengths that we would have been, because we are going to have a lot more offshore, it gives us an opportunity to decarbonise the networks.	Clustering constraints Start-up currents Network operator obligations Improve interaction with customers More dynamic networks Gas network leakage low Electric network losses reducing through closer generation.	Energy networks

Peak time Peak demand is a major issue for both energy suppliers and network operators Peak demand actions only recognised economically within electricity supply and essentially through varying time/price tariffs Tariff differences justified on the cost of electricity generation at different times through the use of more expensive generation capacity Gas storage during the summer making ready for any winter peak periods can justify future time of day or time of year tariff differences Smart metering, is under the ownership and responsibility of the energy supplier and can permit differential rates to be applied technically Network operators and suppliers can help change occupants behaviour through pricing signals or even credits that can be made for not using energy at a particular time using a stick and carrot approach Improvements will allow network operators to receive information on a real time basis and help define the extent of loads To exploit time use of smart metering, household technologies need to change – this could include greater use of thermal or other types of storage either at community or household level. Peak demand is beginning to fall off and is met more and more with the gas fired stations Might have a predominantly base load electric heating but just topping up with gas to avoid those investments At the moment we use one gas turbine for 24 hours and the other just comes in during the day … this effectively gives inefficiencies during start up and close downs Full penetration of heat pumps and EV's to 2030 could increase electricity consumption by 50% and double the peak.......optimising demand response could limit peak increase to 29% ...... smart reduces costs of network investment by at least 50% compared to BAU.	Peak demand major concern Peak demand pricing only for electricity Gas seasonal storage not demand priced Smart metering may include differential pricing Behaviour change through peak time pricing and credits Real time information for load extent Storage at low demand times Base load electric heating and gas top up Optimising demand response to limit peak Network savings through smart metering.	
Future housing 80% reduction impacts:		
Barriers to low carbon solutions: Currently, insufficient carrots and sticks to try and motivate occupants to take up such low carbon measures. Occupants are not necessarily concerned that they could save energy if they were to invest a lot of money in their property in the first instance	Few carrots and sticks for low carbon measures Spending on property for energy	Low carbon market drivers and impacts

Policy mechanisms do not address the value of future avoided electricity or energy demand The majority of low carbon developments to date have been planned and implemented in the public sector Barrier for occupants is the *hassle factor* or getting someone around to improve their homes even though this could make economic sense Available information, knowledge and the reputation of different energy options, technologies and suppliers is important if occupants are to purchase them Both owners and occupants are concerned about the impact on their pockets rather than the environment The construction industry itself is conservative in nature and possibly resistant to change. Developers and builders want to be able to "build and leave" and perceive that low carbon technologies will create both installation and maintenance problems Local authorities consider government policies as barriers and are seen as disjointed with planning policies varying with differences in how they are implemented locally and the manipulation of the planning rules by developers/builders to avoid having to install renewable energy technologies. If people were experiencing difficulties in paying the bills and there was an option of having it on their street …that could be one way …..and if that was then and if that was being met/made by local people rather than by some faceless large utility company that might be a good way of doing it…. yes Essential that the EU regulatory framework and policy instruments are fully consistent and that they address the role of decarbonised electricity in replacing the direct use of fossil fuels Clients are generally unwilling to budget for renewable energy, especially if there is a long payback period. Technology wise we know that this technology will only kick into play in 10 to 15 years' time.	saving not priority Value of future avoided energy not in policy Hassle factor Available information, knowledge and reputation for energy options, technologies and suppliers important Impact on pockets more important than environment Conservative in nature Build and leave mentality Installation and future maintenance issues with low carbon technologies Difference in implementation of planning policies Faceless utilities Need consistency of policy at all levels Long payback period issues Long time frames for next technologies.	
Energy efficiency: Set a target for energy intensity – energy intensity is an indicator driven by economic structure as well as deployment of energy efficiency on the ground	Energy intensity indicator	
Educational issues: Occupants do not understand how their heating system works or how savings can be made. Off-peak cheaper electricity has an advantage and helps change people's behaviour through pricing signals It's getting that across to them it's … an educational consideration to get them to accept that Aims to reduce the burden of fuel cost which in turn is expected to encourage the householders to take up	Understanding of heating systems and savings Pricing signals Cost savings to thermal comfort Take-back effect	Socio-economic

some of the cost savings benefit as improved thermal comfort Evidence shows that the introduction of insulation and central heating leads to increased indoor temperature and improved thermal comfort clearly demonstrating the process of take-back - combined effect of improved building fabric thermal performance – mainly associated with insulation – and occupancy behaviour demanding increased temperature for thermal comfort and less clothing for physical comfort More intelligent solution which is how you interact with those customers so that they have the requirements that they want but at the same time we minimise the impact on our network If we don't manage that new load in a way and an intelligent way with the help of the customer then we would need to reinforce … of course reinforcing our network means that we end up building new assets Some of them use gas for cooking and we are trying to get the gas out of the buildings - what we are trying to do is discourage them from gas and to move to electric units What we have found is that a lot of tenants still think that if the storage heater is on for four hours or a bit overnight using off peak electricity that is OK, they don't realise that they need to leave it on and heat the storage heaters up to a certain level to get the right temperature The other thing that you have to bear in mind is - our residents often enjoy the heat…….. in some homes especially on district heating system ….it can be up in the 70's but if you go into other homes where there is their own gas or electric boiler – it is freezing cold.	Intelligent solutions including customer interaction to reduce network impacts Reducing new network assets through managing loads Enjoy higher temperatures Mistiming energy.	
Fuel poverty: Households living in fuel poverty generally experience poor quality of life and increased health risk from prolonged exposure to cold temperatures Apartment blocks occupants tend to be excluded from wider energy choices and are only able to use what is installed Fuel poverty principally caused by a combination of low income, high energy cost and energy inefficient dwellings. Fuel poverty focus on insulation to improve the thermal performance of buildings, maximising occupants incomes through benefits and provision of a cheaper source of fuel into the property Stakeholders see the way around fuel poverty as being an improvement in home energy performance especially within social, local authority and association housing Fuel poverty variations across the country, definite differences and challenges around the country. In terms of switching of gas to electricity there is no grant … if you do it the other way round electricity to gas	Poor quality of life Health risk Exclusion form wider energy choices Low incomes Inefficient dwellings Home energy performance Varies across the country Different challenges around country Grant less switching Traditional areas of fuel poverty Improved savings insulation Aligning with energy company for	

there is a grant from the point of view of the obligations of the energy companies from the regulator Obviously there will be a limit to the amount of money that people can spend … people can only have so many grants up to that limit and if fuel prices increase what we are going to find is that more people will be dragged into fuel poverty from outside the traditional areas where basically its link to poverty or linked to benefit or retirement Energy or fuel poverty …… there is a scheme called the green deal scheme which is mainly there for fuel poverty/venerable people … the scheme looks at providing support to those with not very good credit ratings …..about a third of the household bill is electricity …the gas portion could be about 1200£…. with good insulation it could knock 20% of that amount Whether we should be looking to see if we could align with an energy company so that we will offer our residents a better deal for duel fuel and for electric What we have to bear in mind is not so much whether electric provides sufficient heat but that 80% of our residents are in fact on benefits….on top of that 30% are pensionable age so they haven't got the money to heat their houses as somebody who is working with a load of excess money and who could just turn up the heating and it's just an extra tenner.	savings Benefits based occupants.	
Well-being and health: Energy improvement programmes aimed at reducing the burden of fuel cost which in turn is expected to encourage occupants to take up some of the cost savings benefit as improved thermal comfort. There is a shift to be honest …the most important point is that I have certainly taken a lot of time trying to engage is health …. I think a lot of the future of driving this forward is in health rather than in the traditional housing side. Future energy agenda considers occupants understanding as to how they use the energy systems, how they spend their time with the property, and the effects that it can have on their health.	Improvements may have contradictory impacts Health as a driving force for energy agenda.	
Decision making: Developers deal with their own issues rather than doing anything collectively The nature of the process is that we would accept the whole of the bid so…. the heating solution would be one consideration but heating solutions must meet what we require in terms of output specifications but that would be taken into consideration along with all or huge number of other things We are trying to get the gas out of the buildings We've done a little bit of research into centralised gas boilers but we found that the cost is a bit over the top for	Selfish intensions Small consideration amongst many others Firm decision to remove gas Research confirms expensive Angle of attack	Stakeholders

us We have got to look at where we are coming from with this We are trying to get the other residents to agree and when we do we will remove the gas mains completely from the building I think we all recognise that there is only so much you can do ….it may not be my problem by the time gas runs out! The key stakeholders are the government as they set the standards and policies and the developers have recently had to dance to their tune.	Agreement before action Recognition of limitations Not always our problem Dancing to their tune.	
Community actions: People are worried about what their carbon footprint is ….. what it is or potentially could be in the future a lot more now So we've managed to get the money back for one or two of them but it's the way that they have been set up at the meters that was the problem If we were looking to having a sizeable chunk of land the priority would be sheltered accommodation so that we could possibly offer people who presently occupy two or three-bedroom houses to move into more suitable accommodation	Carbon footprint concerns Actions on behalf of others Social endeavours.	
Key players: Low income households Those suffering the burden of fuel cost Non-governmental organisations (NGO's) Consumer focused organisations Developers Government offices Energy conservation organisations Organisations at the coalface Housing associations Utility companies Local authorities Customers Manufacturers		

Energy service companies Energy generators Leaseholders Those involved in the supply chain of energy Players operate in their own sphere People have great distrust in organisations are trying to sell you energy and then trying to save you energy at the same time.		

20.2 Emergence of concepts from codes

[Key: # included as concept *Italics covered as inclusive or repeating point]*

Codes	Concepts	Categories (common theme) Planning, Regs, Heat providing, Emission shifting, Networks, Low carbon, Socio, Stakeholders
Cost *Cost effectiveness* *Cheapest capital, highest running cost* #Cost concerns not carbon concerns #Incentives important #Profit significant player #Context of pricing #Future pricing against time usage *Utilising incentives* #Better deals through cooperation #Lock-in *Smart metering may include differential pricing* *Peak demand pricing only for electricity* #Spending on property for energy saving not priority #Long payback period issues #Value of future avoided energy not in policy *Impact on pockets more important than environment* #Build and leave mentality *Pricing signals*	Cost concerns not carbon concerns Profit significant player Context of pricing Value of future avoided energy not in policy Excessive costs and focus on reducing costs Spending on property for energy saving not priority Long payback period issues Build and leave mentality Incentives important Grant-less switching Future pricing against time usage Lock-in for several years Fuel poverty varies across country Low incomes, benefits based occupants and poor tariffs Better deals through cooperation	**Cost** Cost and profit significant Short term view prevails Change through inducements Time value of energy and investments

Aligning with energy company for savings #Fuel poverty varies across the country. #Low incomes *Benefits based occupants.* #Grant less switching #Ensuring correct tariff #High cost of gas pipe installation. #High cost of transformers and switchgear *Reducing costs* *Excessive cost* Off peak cheaper electricity important. Carbon costs Low cost, low maintenance Carbon cost determine fuel type used Conservative in nature Cost savings to thermal comfort	High costs of infrastructure development and renewal	
Gas clean, electric dirty #Gas systems oversized *Gas micro-chp flexible* *Possible higher indoor emissions* *Centralised gas rather than individual* #Requirement for certificates and annual maintenance #Duel fuel technologies. *Gas infrastructure and safety heavy* #Gas first choice #More individual gas to centralised gas #Improving boiler emissions	**(Concepts here moved to HEAT category)**	**Heat**

#In love with gas. *No material alternative to gas* *No second dash for gas.* *Clean fuel* #Shale gas reserves *LNG availability* #Gas seasonal storage not demand priced *City transport emissions comparatively significant* Cooking concerns Gas used for generation Gas network leakage low Firm decision to remove gas		
Localised electricity storage #Ease of installation #Electric fed from any renewable source *Simpler and easier* *New build significant for electric heating* #Electric volume through heat services *Electric heat service penetration small* *Retrofits easier for electric* *Renewables to green future electricity.* *Variable generation locations.* *Electricity always needed* #Recent short term switch to electric heat #Smaller housing units and improved insulation #Private sector initiative #Electric future not only upstream generation *Localised combustion to minimise losses*	Gas first choice, clean, in love with gas, but safety heavy Gas reserves and supply available, not demand priced No material alternative to gas - no second dash for gas Electric heat short term private sector market development thing Gas systems oversized Gas emissions improving, less significant in urban areas than transport Ease and simplicity of installation Move from individual gas to centralised gas Minimising losses through local generation, storage and use	**Heat** Gas widely accepted and valued Centralised heat supply and local generation

#Inefficient homes and electric don't mix *Decentralised electricity and electric heat* *Electric network losses reducing through closer generation.* #Market development thing *Upstream and downstream electric focus needed.* *Flexible in generation source* *Future easy conversion* *Renewable contribution increasing.* Buildings adapting to new technologies Electric system sized exactly Declining sales of resistance equipment Electric supplementing space heating	Inefficient homes and electric don't mix, smaller well insulated do Electric future not only upstream generation Electric always needed and can be fed from any appropriate source Electric heat service small but electric volume through heat services	 Home efficiency and electric heating issues Electric available and adaptable
#Regulation to kill of electricity *SAP works against electricity* #Developers preferences #Renewables used for bargaining #Manipulation of building regulations. *Tightening of regulations* *Difference in implementation of planning policies* #Need consistency of policy at all levels *Tight requirements limit electric* *Government plans* #Massive transformation *Business model change* #Future economics push towards electricity than gas #Speed of change unpredictable	 Regulations to kill off electricity Consistency of policy at all levels Manipulation of building regulations Renewables used as bargaining tool Developers preferences New routes to markets. Future economics push towards electricity than gas Change to involve a massive transformation but its speed unpredictable Localised approaches to energy	**Regulations** Regulations as an energy control mechanism Regulations as a bargaining tool Large change Localised approaches to energy

#New routes to markets. #Small consideration amongst many others *Crystal balling* *Local scenarios.*		
#Peak demand major concern #Clustering constraints #More dynamic networks #Storage at low demand times *Behaviour change through peak time pricing and credits* #Real time information for load extent *Optimising demand response to limit peak* #Network savings through smart metering *Reducing new network assets through managing loads* *Mistiming energy* *Over capacity or consumer demand flexibility* *Demand profile changes* *Clustering effects of mono-systems* *Proactive energy use management.*	Peak demand is major concern Peak pricing, credits and mistiming Changing of demand profile through demand flexibility, pricing and management Fuels working together Clustering effects and constraints Dynamic network using real-time information and pro-active energy use management Network savings through smart use Heat storage at low demand times Obligations of network operators	**Demand** Peak demand issues Clustering impacts Network management, storage and control concerns

Reduction in infrastructure requirements #Base load electric heating and gas top up *Start-up currents* *Network operator obligations* North to south supply		
#Improve interaction with customers #Available information, knowledge and reputation for energy options, technologies and suppliers important *Intelligent solutions including customer interaction to reduce network impacts* #Understanding of heating systems and savings #Take-back effect *Enjoy higher temperatures* #Network initiators *Interaction* *Interaction of players* #Public perception and efficiency *Agreement before action* *Recognition of limitations* #Selfish intensions #Not for always our problem *Dancing to their tune.* *Actions on behalf of others* *Poor quality of life* *Health risk* #Exclusion from wider energy choices #Hassle factor #Traditional areas of fuel poverty	Customer interaction and agreement to reduce network impacts Better understanding and information of system, savings and limitations Sense of powerlessness and others agendas Faceless and exploitative private organisations and utilities Network initiators Locally led and supported initiatives Exclusion from wider energy choices Poor quality of life and health issues from fuel poverty Hassle factor, public perception and efficiency as key motivation issues Improvements used as take back and higher temperatures Not for always our problem	**Interaction** Interaction with consumer Locally led network initiators Exclusion from choice Ownership and motivation

Health as a driving force for energy agenda. #Private management. *Led locally by communities* *Local authority led* *Faceless utilities* Research confirms expensive Angle of attack Social endeavours Different fuel poverty challenges around country Improvements may have contradictory impacts		
#New technologies for system and demand management *Less focus on space heating more on water heating* #Heat storage required *Centralised systems* *Reduced storage needs* *Hot water storage effective* #Good insulation *Ensuring home efficiency* #Centralised systems rather than individual *Electric controls support control and management* #Installation and future maintenance issues with low carbon technologies *Long time frames for next technologies.* #Switch through technology changes *Technology progress unclear* *Inefficient dwellings* *Improved savings insulation* *Well planned, effective and efficient installed*	Insulation playing key role Well planned, effective and efficient installed technologies. Centralised systems rather than individual Heat and electric storage at local and individual levels New technologies applied to system control and management Timeframes and time responsibilities with renewable technologies Technologies changes promote switches Duel fuel technologies and approaches	**Technology** [Duplicate] [Duplicate] Renewable timeframes and time responsibilities Technology switches and mutual fuelling

technologies. Limiting space for plant. Material and manufacturing improvements Home energy performance		
Energy intensity indicator. Support within social housing Inner city trend Recognition of di and tri-lemmas	Clustering effects of social and inner city housing	**Bigger picture stuff** [Duplicate]
#Few carrots and sticks for low carbon measures *Carbon footprint concerns* *Local emissions forgotten* #Less pollution but more concerns	Few carrots and sticks for low carbon measures Less pollution but more concerns	**Carbon** Few carrots and sticks from carbon measures

21 Appendix 11: Quantitative data processing

21.1 Quantitative normalised data for each system used in MCDA.

System	Electric panel	Electric storage	ASHP	Gas boiler	Combined gas and electric	District heating	CHP	Solar thermal + gas
ADP elements	0.1813	0.1768	0.1921	0.0573	0.1302	0.084	0.0905	0.0879
ADP fossil	0.2001	0.2101	0.1545	0.071	0.1476	0.0768	0.0717	0.0681
AP	0.2636	0.2765	0.2061	0.0109	0.1564	0.0324	0.0394	0.0147
EP	0.2285	0.2396	0.182	0.04	0.1501	0.0565	0.0571	0.0462
FAETP	0.2021	0.2082	0.1951	0.0291	0.1188	0.0825	0.0946	0.0696
GWP	0.1967	0.2065	0.1518	0.074	0.1471	0.079	0.0739	0.071
HTP	0.2159	0.2241	0.2032	0.022	0.1235	0.0765	0.0803	0.0545
MAETP	0.2704	0.2841	0.2112	0.0055	0.1572	0.0284	0.0301	0.013
ODP	0.1561	0.1639	0.1444	0.1028	0.1258	0.1026	0.0977	0.1066
POCP	0.2447	0.2567	0.1931	0.0268	0.1523	0.0443	0.0506	0.0315
TETP	0.2577	0.2694	0.2085	0.0066	0.1459	0.0444	0.047	0.0204
Indoor CO	0.1789	0.1789	0.1789	0.4313	0.1789	0.1789	0.1789	0.2204
Indoor CO2	0.0638	0.0638	0.0638	0.2239	0.0638	0.0638	0.0638	0.1835
Indoor NO2	0.2839	0.2839	0.2839	0.3651	0.2839	0.2839	0.2839	0.3975
Indoor SO2	0.3486	0.3486	0.3486	0.3696	0.3486	0.3486	0.3486	0.3354
Capital costs of system	0.0504	0.0684	0.113	0.0731	0.0762	0.2001	0.2433	0.1755
Energy costs of system	0.2019	0.1802	0.1492	0.1011	0.1526	0.0783	0.0384	0.0983
Operation and maintenance costs of system	0.0487	0.0478	0.0879	0.1175	0.0597	0.2101	0.2532	0.1751
System costs per KWh	0.2047	0.1783	0.1978	0.086	0.1367	0.0719	0.0407	0.0839
Diversity of heat	0.1223	0.1266	0.1266	0.1354	0.1135	0.1266	0.131	0.1179
Development implications	0.1461	0.1517	0.1124	0.1348	0.118	0.1067	0.1124	0.118
Application of technologies	0.1096	0.1096	0.1507	0.0959	0.0959	0.137	0.137	0.1644
Carbon measures	0.1667	0.1667	0.125	0.1667	0.125	0.0833	0.0833	0.0833
System effectiveness and efficiency	0.1939	0.1633	0.1224	0.0816	0.1735	0.0816	0.0816	0.102
Safety, regulations and uses	0.1081	0.1081	0.1081	0.1441	0.1171	0.1351	0.1351	0.1441
Heat technologies and energy sources	0.1367	0.1367	0.123	0.139	0.123	0.1185	0.1139	0.1093
Heat control and management	0.1121	0.1121	0.1121	0.1466	0.1121	0.1293	0.1293	0.1466
Fuel resilience	0.1287	0.1287	0.1287	0.1637	0.117	0.1053	0.1053	0.1228
Social timing	0.1201	0.1081	0.1261	0.1291	0.1231	0.1321	0.1351	0.1261
Demand implications	0.1505	0.129	0.1505	0.1452	0.1183	0.1075	0.1075	0.0914
Interaction and ownership	0.1245	0.1245	0.1245	0.1245	0.1205	0.1285	0.1285	0.1245
System perceptions and experience	0.1512	0.1512	0.1512	0.1111	0.1265	0.0988	0.0988	0.1111

Acceptability of systems	0.1356	0.1356	0.1441	0.1271	0.1271	0.1271	0.1017	0.1017
Low income-high cost measure	0.1724	0.1552	0.1207	0.1207	0.1322	0.0977	0.0977	0.1034

22 Appendix 12: Multi-criteria decision analysis robustness diagrams

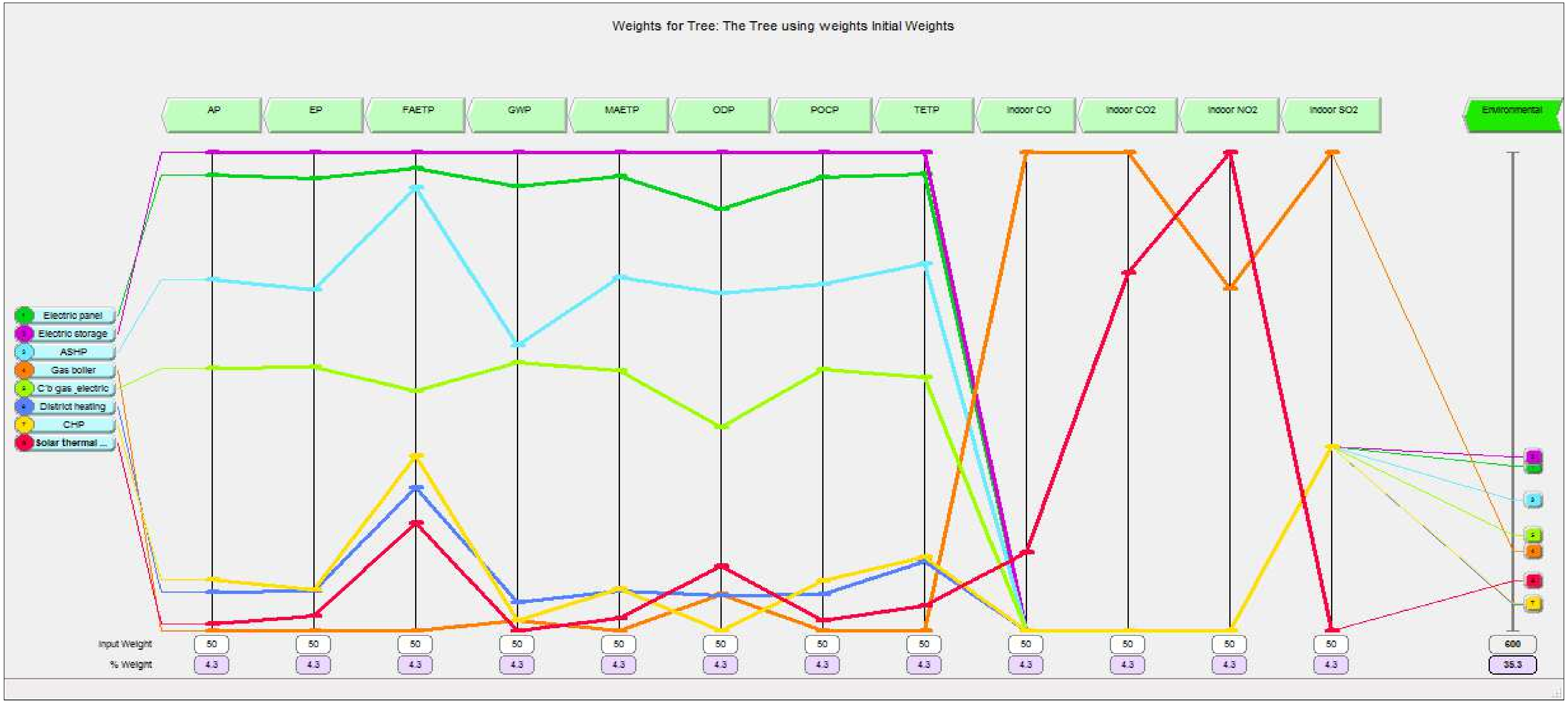

Figure 192 Ranking of systems environmental impacts according to MCDA and where environmental impacts are most important.

[Equal weighting, lower values are better].

Figure 193 Ranking of systems techno-economic impacts according to MCDA and where environmental impacts are most important.

[Equal weighting, lower values are better].

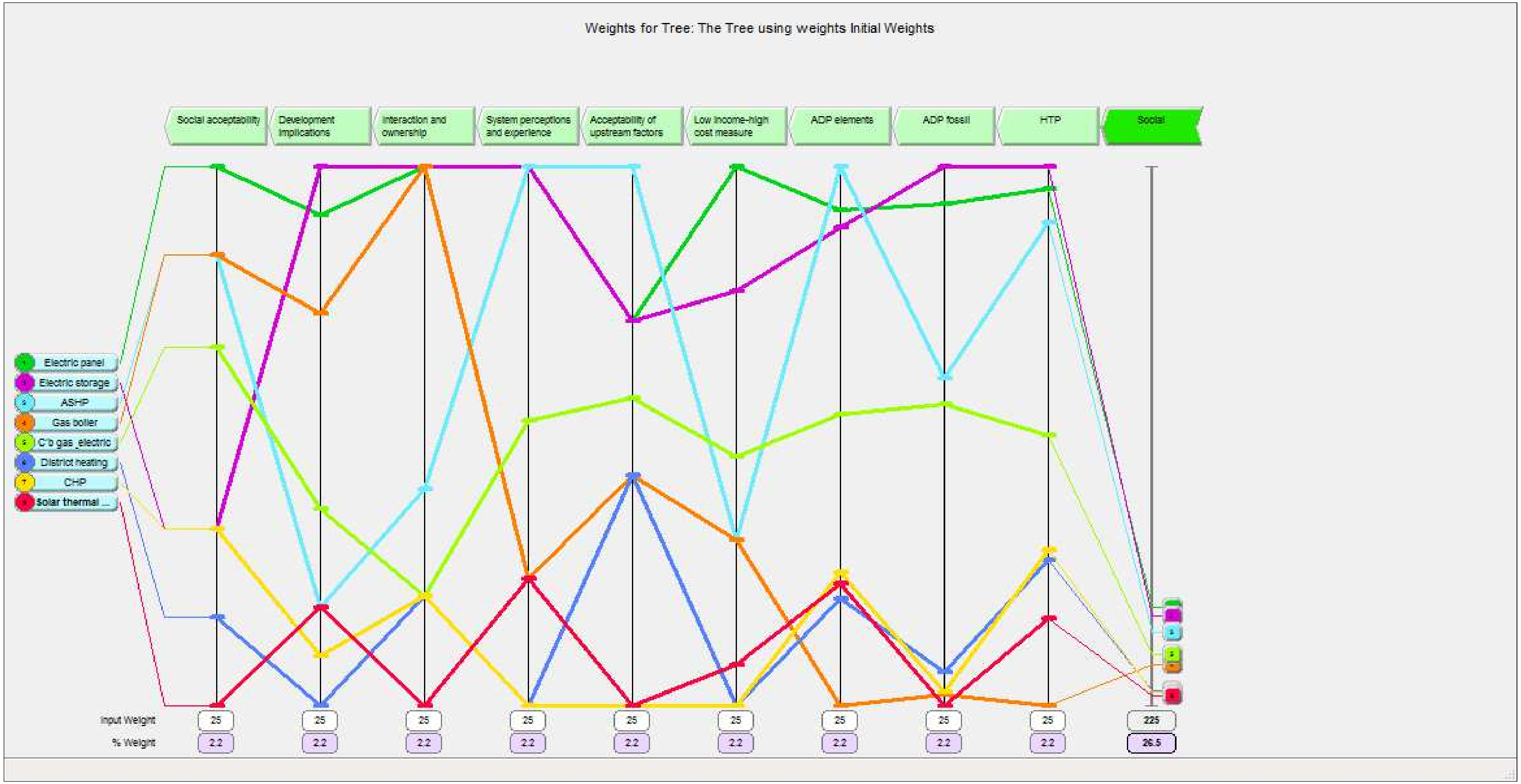

Figure 194 Ranking of systems social impacts according to MCDA and where <u>*environmental impacts*</u> *are most important.*

[Equal weighting, lower values are better].

Figure 195 Ranking of systems environmental impacts according to MCDA and where <u>*techno-economic*</u> *impacts are most important.*

[Equal weighting, lower values are better].

Figure 196 Ranking of systems environmental impacts according to MCDA and where <u>techno-economic</u> impacts are most important.

[Equal weighting, lower values are better].

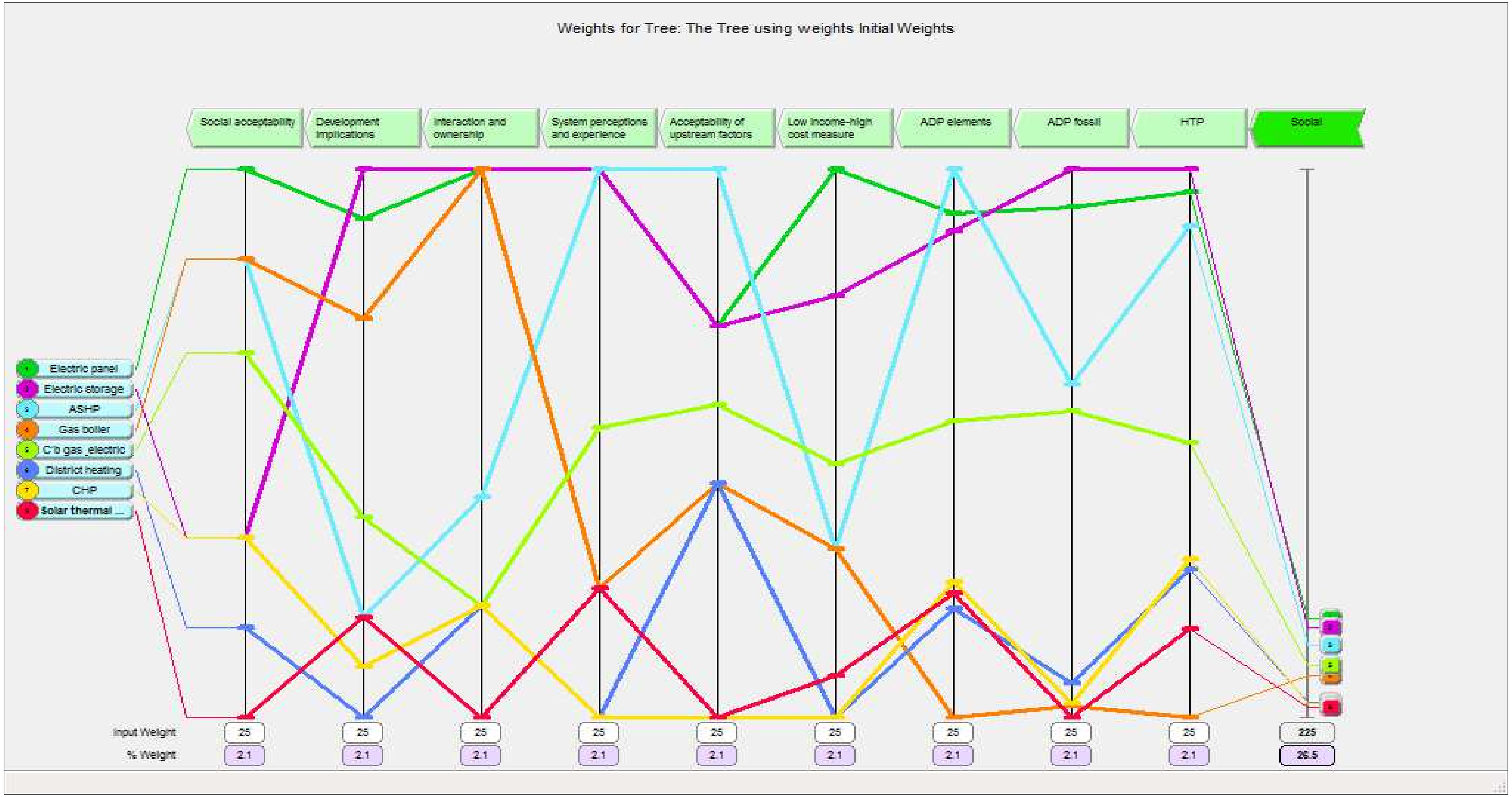

Figure 197 Ranking of systems environmental impacts according to MCDA and where techno-economic impacts are most important.

[Equal weighting, lower values are better]

Figure 198 Ranking of systems environmental impacts according to MCDA and where ***social impacts*** *are most important.*

[Equal weighting, lower values are better].

Figure 199 Ranking of systems environmental impacts according to MCDA and where <u>social impacts</u> are most important.

[Equal weighting, lower values are better].

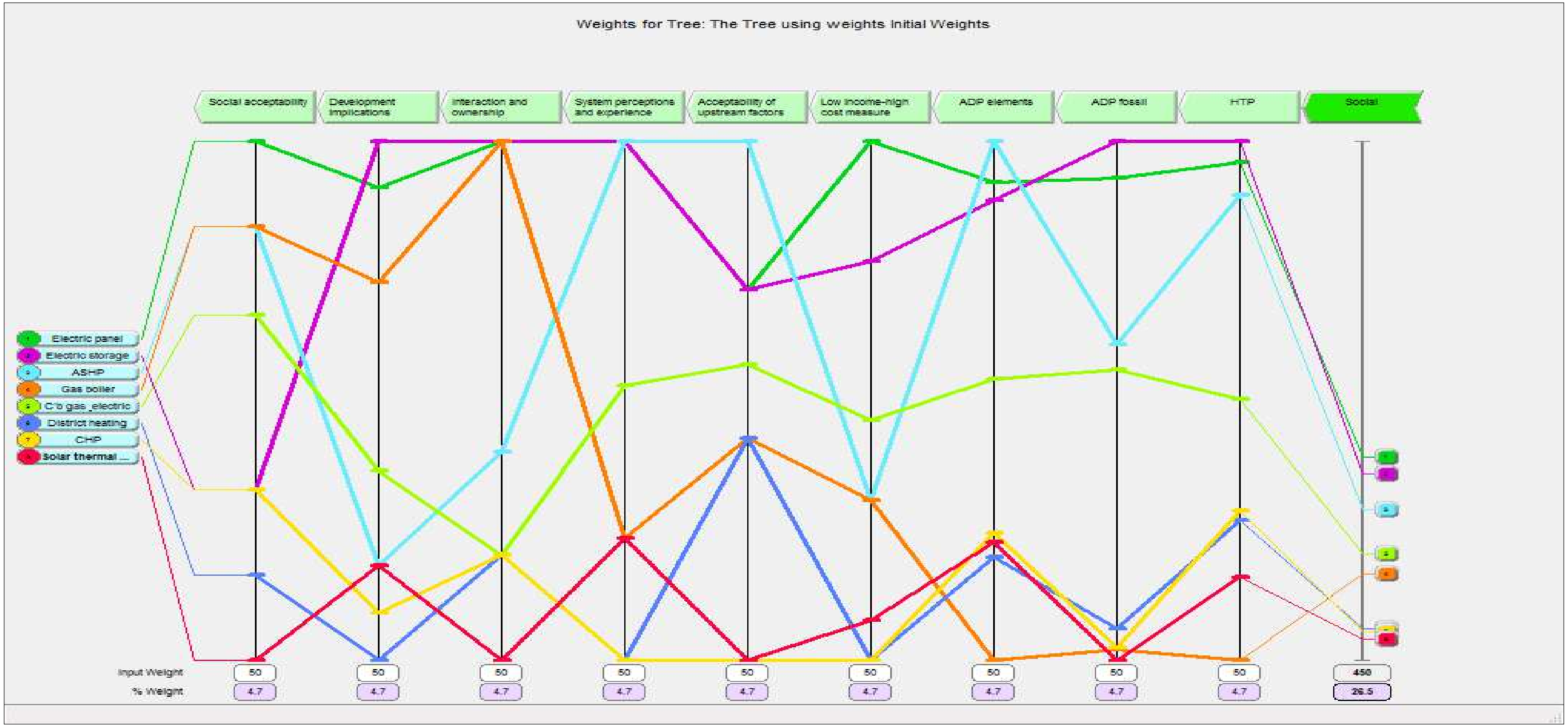

Figure 200 Ranking of systems environmental impacts according to MCDA and where social impacts are most important.

[Equal weighting, lower values are better]

23 Appendix 13: Population and household data used for scenario development

23.1 Population data for UK as used in national scenarios.

Source: (ONS, 2011).

Population (data from DECC pathways)	Reference	Scenario 1	Scenario 2	Scenario 3
2007	60973000	60973000	60973000	60973000
2010	62222403	62222403	62222403	62222403
2015	64344156	64344156	64344156	64344156
2020	66521962	66521962	66521962	66521962
2025	68647528	68647528	68647528	68647528
2030	70575666	70575666	70575666	70575666
2035	72278230	72278230	72278230	72278230
2040	73853253	73853253	73853253	73853253
2045	75356458	75356458	75356458	75356458
2050	76789483	76789483	76789483	76789483

23.2 Household data for UK as used in national scenarios.

Source: (DCLG, 2013; DECC, 2012a; ONS, 2011).

Households (data from DECC pathways)	Reference	Scenario 1	Scenario 2	Scenario 3
2007	26042600	26042600	26042600	26042600
2010	26917400	26917400	26917400	26917400
2015	28469000	28469000	28469000	28469000
2020	30004800	30004800	30004800	30004800
2025	31434800	31434800	31434800	31434800
2030	32744800	32744800	32744800	32744800
2035	34415114	34415114	34415114	34415114
2040	36170631	36170631	36170631	36170631
2045	38015696	38015696	38015696	38015696
2050	39954879	39954879	39954879	39954879

23.3 Household data as used in urban scenarios.

Households (Urban)	Urban One	Urban Two	As % of total UK	As % of total UK
2007	460824	460824	1.77%	1.77%
2010	476304	476304	1.77%	1.77%
2015	479719	479719	1.69%	1.69%
2020	483133	483133	1.61%	1.61%
2025	486548	486548	1.55%	1.55%
2030	489962	489962	1.50%	1.50%
2035	510484	510484	1.48%	1.48%
2040	531006	531006	1.47%	1.47%
2045	551527	551527	1.45%	1.45%
2050	572049	572049	1.43%	1.43%

24 Appendix 14: Life cycle environmental emissions from electricity generation – as used in scenario development

24.1 Reference – national scenario - Lifecycle environmental emissions from electricity generation.

Reference	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh
ADP elements [kg Sb-Equiv.]	1.98E-08	2.71E-08	8.30E-08	9.28E-08	8.42E-08	7.17E-08	6.15E-08	4.94E-08	4.16E-08	4.16E-08
ADP fossil (ADP fossil) [MJ]	6.70E+00	6.62E+00	5.87E+00	5.57E+00	5.00E+00	4.51E+00	4.92E+00	4.90E+00	5.03E+00	5.03E+00
AP [kg SO2-Equiv.]	3.93E-03	3.88E-03	4.59E-04	4.03E-04	3.11E-04	2.36E-04	2.59E-04	2.46E-04	2.50E-04	2.50E-04
EP [kg Phosphate-Equiv.]	1.91E-04	1.89E-04	5.78E-05	5.23E-05	4.07E-05	3.04E-05	3.28E-05	2.95E-05	2.94E-05	2.94E-05
FAETP [kg DCB-Equiv.]	4.87E-03	4.81E-03	7.19E-03	6.02E-03	4.23E-03	3.29E-03	2.64E-03	2.24E-03	2.00E-03	2.00E-03
GWP [kg CO2-Equiv.]	5.80E-01	5.73E-01	4.30E-01	3.99E-01	3.60E-01	3.26E-01	3.59E-01	3.56E-01	3.68E-01	3.68E-01
HTP [kg DCB-Equiv.]	6.28E-02	6.15E-02	3.73E-02	2.92E-02	1.79E-02	1.17E-02	8.20E-03	6.51E-03	5.44E-03	5.44E-03
MAETP [kg DCB-Equiv.]	3.98E+01	3.93E+01	1.34E+02	1.02E+02	5.46E+01	1.91E+01	1.57E+01	1.22E+01	1.09E+01	1.09E+01
ODP [kg R11-Equiv.]	1.06E-08	1.02E-08	3.11E-08	3.55E-08	4.13E-08	4.60E-08	5.12E-08	5.17E-08	5.35E-08	5.35E-08
POCP (kg ethene-eq./KWh)	2.04E-04	2.02E-04	6.08E-05	6.07E-05	5.89E-05	5.59E-05	6.29E-05	6.13E-05	6.31E-05	6.31E-05
TETP (kg dichlorobenzene-eq./KWh)	6.59E-04	6.62E-04	6.73E-04	5.86E-04	4.13E-04	2.87E-04	2.55E-04	2.18E-04	1.99E-04	1.99E-04
	2008	2010	2015	2020	2025	2030	2035	2040	2045	2050
	216.15	216.36	158.27	154.09	148.14	143.21	166.07	175.71	189.52	203.34
	58.95	59.01	43.16	42.02	40.40	39.06	45.29	47.92	51.69	55.46

24.2 High electricity scenario - Lifecycle environmental emissions from electricity generation.

High Electricity	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh
ADP elements [kg Sb-Equiv.]	1.99E-08	2.83E-08	1.03E-07	1.58E-07	1.93E-07	2.26E-07	3.35E-07	2.96E-07	3.23E-07	3.23E-07
ADP fossil (ADP fossil) [MJ]	6.71E+00	6.50E+00	5.51E+00	4.77E+00	3.37E+00	2.05E+00	1.75E+00	1.40E+00	1.45E+00	1.45E+00
AP [kg SO2-Equiv.]	3.94E-03	3.82E-03	4.51E-04	3.85E-04	2.51E-04	1.46E-04	1.41E-04	1.25E-04	1.35E-04	1.35E-04
EP [kg Phosphate-Equiv.]	1.91E-04	1.86E-04	5.85E-05	5.47E-05	4.13E-05	3.27E-05	3.57E-05	3.49E-05	3.72E-05	3.72E-05
FAETP [kg DCB-Equiv.]	4.90E-03	5.07E-03	8.17E-03	8.43E-03	8.03E-03	9.21E-03	1.05E-02	1.12E-02	1.18E-02	1.18E-02
GWP [kg CO2-Equiv.]	5.80E-01	5.62E-01	4.02E-01	3.36E-01	2.29E-01	1.23E-01	8.25E-02	4.94E-02	3.34E-02	3.34E-02
HTP [kg DCB-Equiv.]	6.29E-02	6.20E-02	4.18E-02	4.02E-02	3.53E-02	3.87E-02	4.50E-02	4.91E-02	5.44E-02	5.44E-02
MAETP [kg DCB-Equiv.]	3.99E+01	3.93E+01	1.41E+02	1.19E+02	6.92E+01	3.81E+01	4.49E+01	4.57E+01	5.27E+01	5.27E+01
ODP [kg R11-Equiv.]	1.07E-08	1.03E-08	2.58E-08	2.38E-08	2.24E-08	1.82E-08	1.45E-08	1.10E-08	1.07E-08	1.07E-08
POCP (kg ethene-eq./KWh)	2.04E-04	1.98E-04	5.58E-05	4.95E-05	3.80E-05	2.54E-05	2.21E-05	1.74E-05	1.75E-05	1.75E-05
TETP (kg dichlorobenzene-eq./KWh)	6.62E-04	6.70E-04	7.44E-04	7.58E-04	6.45E-04	6.43E-04	7.38E-04	7.63E-04	7.86E-04	7.86E-04
	2008.0	2010.0	2015.0	2020.0	2025.0	2030.0	2035.0	2040.0	2045	2050.0
	216.3	198.9	131.6	114.4	84.3	46.8	29.5	16.0	12.05	8.1
	59.0	54.2	35.9	31.2	23.0	12.8	8.0	4.4	3.29	2.2

24.3 National grid scenario - Lifecycle environmental emissions from electricity generation.

National Grid	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh
ADP elements [kg Sb-Equiv.]	1.99E-08	2.78E-08	9.73E-08	1.37E-07	1.66E-07	1.80E-07	2.73E-07	2.29E-07	2.55E-07	2.55E-07
ADP fossil (ADP fossil) [MJ]	6.71E+00	6.55E+00	5.78E+00	5.03E+00	3.88E+00	2.92E+00	3.15E+00	2.89E+00	3.15E+00	3.15E+00
AP [kg SO2-Equiv.]	3.94E-03	3.85E-03	4.69E-04	3.93E-04	2.83E-04	2.03E-04	2.39E-04	2.38E-04	2.76E-04	2.76E-04
EP [kg Phosphate-Equiv.]	1.91E-04	1.88E-04	6.00E-05	5.41E-05	4.46E-05	3.81E-05	4.73E-05	4.90E-05	5.69E-05	5.69E-05
FAETP [kg DCB-Equiv.]	4.90E-03	4.98E-03	7.94E-03	8.02E-03	9.57E-03	9.45E-03	1.12E-02	1.23E-02	1.36E-02	1.36E-02
GWP [kg CO2-Equiv.]	5.80E-01	5.67E-01	4.22E-01	3.56E-01	2.55E-01	1.58E-01	1.24E-01	8.30E-02	5.14E-02	5.14E-02
HTP [kg DCB-Equiv.]	6.29E-02	6.18E-02	4.13E-02	3.90E-02	4.56E-02	4.42E-02	5.54E-02	6.26E-02	7.35E-02	7.35E-02
MAETP [kg DCB-Equiv.]	3.99E+01	3.93E+01	1.45E+02	1.15E+02	7.80E+01	5.62E+01	8.31E+01	9.28E+01	1.18E+02	1.18E+02
ODP [kg R11-Equiv.]	1.07E-08	1.03E-08	2.71E-08	2.78E-08	2.84E-08	2.40E-08	2.08E-08	1.64E-08	1.40E-08	1.40E-08
POCP (kg ethene-eq./KWh)	2.04E-04	2.00E-04	5.83E-05	5.30E-05	4.37E-05	3.35E-05	3.39E-05	2.90E-05	2.93E-05	2.93E-05
TETP (kg dichlorobenzene-eq./KWh)	6.62E-04	6.68E-04	7.38E-04	7.08E-04	6.78E-04	6.42E-04	7.96E-04	8.49E-04	9.50E-04	9.50E-04
	2008	2010	2015	2020	2025	2030	2035	2040	2045	2050
	216.33	206.01	142.48	125.16	96.26	62.85	48.03	31.29	23.78	16.27
	59.00	56.19	38.86	34.14	26.25	17.14	13.10	8.53	6.48	4.44

24.4 Markal scenario - Lifecycle environmental emissions from electricity generation.

Markal	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh
ADP elements [kg Sb-Equiv.]	1.99E-08	2.89E-08	9.36E-08	1.20E-07	1.29E-07	1.49E-07	1.91E-07	2.06E-07	2.08E-07	2.08E-07
ADP fossil (ADP fossil) [MJ]	6.71E+00	6.52E+00	5.84E+00	5.16E+00	4.03E+00	3.06E+00	3.24E+00	2.78E+00	2.99E+00	2.99E+00
AP [kg SO2-Equiv.]	3.94E-03	3.83E-03	4.75E-04	4.05E-04	2.90E-04	2.09E-04	2.46E-04	2.38E-04	2.63E-04	2.63E-04
EP [kg Phosphate-Equiv.]	1.91E-04	1.87E-04	6.04E-05	5.48E-05	4.34E-05	3.69E-05	4.57E-05	4.69E-05	5.07E-05	5.07E-05
FAETP [kg DCB-Equiv.]	4.90E-03	5.06E-03	7.93E-03	8.03E-03	8.15E-03	9.52E-03	1.16E-02	1.31E-02	1.38E-02	1.38E-02
GWP [kg CO2-Equiv.]	5.80E-01	5.64E-01	4.26E-01	3.64E-01	2.67E-01	1.68E-01	1.28E-01	6.78E-02	4.91E-02	4.91E-02
HTP [kg DCB-Equiv.]	6.29E-02	6.21E-02	4.16E-02	4.00E-02	3.94E-02	4.65E-02	6.05E-02	7.06E-02	7.73E-02	7.73E-02
MAETP [kg DCB-Equiv.]	3.99E+01	3.93E+01	1.48E+02	1.20E+02	7.83E+01	5.70E+01	8.60E+01	9.81E+01	1.13E+02	1.13E+02
ODP [kg R11-Equiv.]	1.07E-08	1.04E-08	2.72E-08	2.79E-08	2.84E-08	2.62E-08	2.25E-08	1.58E-08	1.52E-08	1.52E-08
POCP (kg ethene-eq./KWh)	2.04E-04	1.99E-04	5.88E-05	5.39E-05	4.48E-05	3.50E-05	3.46E-05	2.71E-05	2.79E-05	2.79E-05
TETP (kg dichlorobenzene-eq./KWh)	6.62E-04	6.69E-04	7.38E-04	7.09E-04	6.15E-04	6.15E-04	7.86E-04	8.53E-04	9.05E-04	9.05E-04
	2008	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	216.33	199.58	139.85	121.72	93.30	60.21	42.22	19.55	**16.81**	14.07
	59.00	54.43	38.14	33.20	25.45	16.42	11.51	5.33	**4.58**	3.84

24.5 Reference – Urban scenario - Lifecycle environmental emissions from electricity generation.

Reference	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh
ADP elements [kg Sb-Equiv.]	1.98E-08	2.71E-08	8.30E-08	9.28E-08	8.42E-08	7.17E-08	6.15E-08	4.94E-08	4.16E-08	4.16E-08
ADP fossil (ADP fossil) [MJ]	6.70E+00	6.62E+00	5.87E+00	5.57E+00	5.00E+00	4.51E+00	4.92E+00	4.90E+00	5.03E+00	5.03E+00
AP [kg SO2-Equiv.]	3.93E-03	3.88E-03	4.59E-04	4.03E-04	3.11E-04	2.36E-04	2.59E-04	2.46E-04	2.50E-04	2.50E-04
EP [kg Phosphate-Equiv.]	1.91E-04	1.89E-04	5.78E-05	5.23E-05	4.07E-05	3.04E-05	3.28E-05	2.95E-05	2.94E-05	2.94E-05
FAETP [kg DCB-Equiv.]	4.87E-03	4.81E-03	7.19E-03	6.02E-03	4.23E-03	3.29E-03	2.64E-03	2.24E-03	2.00E-03	2.00E-03
GWP [kg CO2-Equiv.]	5.80E-01	5.73E-01	4.30E-01	3.99E-01	3.60E-01	3.26E-01	3.59E-01	3.56E-01	3.68E-01	3.68E-01
HTP [kg DCB-Equiv.]	6.28E-02	6.15E-02	3.73E-02	2.92E-02	1.79E-02	1.17E-02	8.20E-03	6.51E-03	5.44E-03	5.44E-03
MAETP [kg DCB-Equiv.]	3.98E+01	3.93E+01	1.34E+02	1.02E+02	5.46E+01	1.91E+01	1.57E+01	1.22E+01	1.09E+01	1.09E+01
ODP [kg R11-Equiv.]	1.06E-08	1.02E-08	3.11E-08	3.55E-08	4.13E-08	4.60E-08	5.12E-08	5.17E-08	5.35E-08	5.35E-08
POCP (kg ethene-eq./KWh)	2.04E-04	2.02E-04	6.08E-05	6.07E-05	5.89E-05	5.59E-05	6.29E-05	6.13E-05	6.31E-05	6.31E-05
TETP (kg dichlorobenzene-eq./KWh)	6.59E-04	6.62E-04	6.73E-04	5.86E-04	4.13E-04	2.87E-04	2.55E-04	2.18E-04	1.99E-04	1.99E-04
	2008	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	216.15	**216.36**	**158.27**	**154.09**	**148.14**	**143.21**	**166.07**	**175.71**	**189.52**	**203.34**
	58.95	**59.01**	**43.16**	**42.02**	**40.40**	**39.06**	**45.29**	**47.92**	**51.69**	**55.46**

24.6 Urban One scenario - Lifecycle environmental emissions from electricity generation.

Urban One	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh
ADP elements [kg Sb-Equiv.]	1.99E-08	2.83E-08	1.03E-07	1.58E-07	1.93E-07	2.26E-07	3.35E-07	2.96E-07	3.23E-07	3.23E-07
ADP fossil (ADP fossil) [MJ]	6.71E+00	6.50E+00	5.51E+00	4.77E+00	3.37E+00	2.05E+00	1.75E+00	1.40E+00	1.45E+00	1.45E+00
AP [kg SO2-Equiv.]	3.94E-03	3.82E-03	4.51E-04	3.85E-04	2.51E-04	1.46E-04	1.41E-04	1.25E-04	1.35E-04	1.35E-04
EP [kg Phosphate-Equiv.]	1.91E-04	1.86E-04	5.85E-05	5.47E-05	4.13E-05	3.27E-05	3.57E-05	3.49E-05	3.72E-05	3.72E-05
FAETP [kg DCB-Equiv.]	4.90E-03	5.07E-03	8.17E-03	8.43E-03	8.03E-03	9.21E-03	1.05E-02	1.12E-02	1.18E-02	1.18E-02
GWP [kg CO2-Equiv.]	5.80E-01	5.62E-01	4.02E-01	3.36E-01	2.29E-01	1.23E-01	8.25E-02	4.94E-02	3.34E-02	3.34E-02
HTP [kg DCB-Equiv.]	6.29E-02	6.20E-02	4.18E-02	4.02E-02	3.53E-02	3.87E-02	4.50E-02	4.91E-02	5.44E-02	5.44E-02
MAETP [kg DCB-Equiv.]	3.99E+01	3.93E+01	1.41E+02	1.19E+02	6.92E+01	3.81E+01	4.49E+01	4.57E+01	5.27E+01	5.27E+01
ODP [kg R11-Equiv.]	1.07E-08	1.03E-08	2.58E-08	2.38E-08	2.24E-08	1.82E-08	1.45E-08	1.10E-08	1.07E-08	1.07E-08
POCP (kg ethene-eq./KWh)	2.04E-04	1.98E-04	5.58E-05	4.95E-05	3.80E-05	2.54E-05	2.21E-05	1.74E-05	1.75E-05	1.75E-05
TETP (kg dichlorobenzene-eq./KWh)	6.62E-04	6.70E-04	7.44E-04	7.58E-04	6.45E-04	6.43E-04	7.38E-04	7.63E-04	7.86E-04	7.86E-04
	2008	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	216.33	198.90	131.56	114.35	84.25	46.76	29.48	16.00	**12.05**	8.09
	59.00	54.25	35.88	31.19	22.98	12.75	8.04	4.36	**3.29**	2.21

24.7 Urban Two scenario - Lifecycle environmental emissions from electricity generation.

Urban Two	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh	Impacts per kWh
ADP elements [kg Sb-Equiv.]	1.99E-08	2.89E-08	9.36E-08	1.20E-07	1.29E-07	1.49E-07	1.91E-07	2.06E-07	2.08E-07	2.08E-07
ADP fossil (ADP fossil) [MJ]	6.71E+00	6.52E+00	5.84E+00	5.16E+00	4.03E+00	3.06E+00	3.24E+00	2.78E+00	2.99E+00	2.99E+00
AP [kg SO2-Equiv.]	3.94E-03	3.83E-03	4.75E-04	4.05E-04	2.90E-04	2.09E-04	2.46E-04	2.38E-04	2.63E-04	2.63E-04
EP [kg Phosphate-Equiv.]	1.91E-04	1.87E-04	6.04E-05	5.48E-05	4.34E-05	3.69E-05	4.57E-05	4.69E-05	5.07E-05	5.07E-05
FAETP [kg DCB-Equiv.]	4.90E-03	5.06E-03	7.93E-03	8.03E-03	8.15E-03	9.52E-03	1.16E-02	1.31E-02	1.38E-02	1.38E-02
GWP [kg CO2-Equiv.]	5.80E-01	5.64E-01	4.26E-01	3.64E-01	2.67E-01	1.68E-01	1.28E-01	6.78E-02	4.91E-02	4.91E-02
HTP [kg DCB-Equiv.]	6.29E-02	6.21E-02	4.16E-02	4.00E-02	3.94E-02	4.65E-02	6.05E-02	7.06E-02	7.73E-02	7.73E-02
MAETP [kg DCB-Equiv.]	3.99E+01	3.93E+01	1.48E+02	1.20E+02	7.83E+01	5.70E+01	8.60E+01	9.81E+01	1.13E+02	1.13E+02
ODP [kg R11-Equiv.]	1.07E-08	1.04E-08	2.72E-08	2.79E-08	2.84E-08	2.62E-08	2.25E-08	1.58E-08	1.52E-08	1.52E-08
POCP (kg ethene-eq./KWh)	2.04E-04	1.99E-04	5.88E-05	5.39E-05	4.48E-05	3.50E-05	3.46E-05	2.71E-05	2.79E-05	2.79E-05
TETP (kg dichlorobenzene-eq./KWh)	6.62E-04	6.69E-04	7.38E-04	7.09E-04	6.15E-04	6.15E-04	7.86E-04	8.53E-04	9.05E-04	9.05E-04
	2008	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
	216.15	216.36	158.27	154.09	148.14	143.21	166.07	175.71	**189.52**	203.34
	58.95	59.01	43.16	42.02	40.40	39.06	45.29	47.92	**51.69**	55.46

25 Appendix 15: Electricity production, technology mix and description for scenario analysis

25.1 Technology mix for UK electricity supply for Reference National and Urban scenario.

Reference	Percentage of Technology to Electricity Mix				
Year	**2010**	**2020**	**2030**	**2040**	**2050**
Electricity (GWh)	387,400	416,600	465,800	520,800	583,700
MtC limit	54.53	16.07	0.05	0.05	0.05
Nuclear	13.6%	6.1%	1.8%	0.0%	0.0%
Coal	37.4%	21.9%	2.4%	0.9%	0.8%
Natural Gas	43.4%	57.2%	81.9%	93.1%	96.4%
Oil	0.6%	0.0%	0.0%	0.0%	0.0%
Wind Onshore	2.7%	6.0%	4.7%	1.4%	0.0%
Wind Offshore	1.1%	4.9%	5.7%	1.5%	0.0%
Solar	0.0%	0.0%	0.0%	0.0%	0.0%
Marine	0.0%	0.1%	0.1%	0.0%	0.0%
Biomass	0.0%	0.0%	0.0%	0.0%	0.0%
Hydro	1.4%	1.3%	1.1%	1.0%	0.9%
Coal CCS	0.0%	1.9%	1.7%	1.5%	1.4%
Gas CCS	0.0%	0.7%	0.6%	0.6%	0.5%
Imports	0.0%	0.0%	0.0%	0.0%	0.0%
Total:	**100%**	**100%**	**100%**	**100%**	**100%**

25.2 Technology mix for UK electricity supply for High electricity and Urban One scenario.

High Electricity	Percentage of Technology to Electricity Mix				
Year	**2010**	**2020**	**2030**	**2040**	**2050**
Electricity (GWh)	363,000	371,500	433,500	473,700	529,700
MtC limit	54.53	16.07	0.05	0.05	0.05
Nuclear	14.5%	9.2%	11.8%	16.1%	20.8%
Coal	36.6%	24.6%	2.5%	1.0%	0.9%
Natural Gas	42.6%	35.6%	24.7%	5.7%	0.0%
Oil	0.6%	0.0%	0.0%	0.0%	0.0%
Wind Onshore	3.2%	12.8%	16.9%	15.8%	14.1%
Wind Offshore	1.1%	13.1%	35.6%	45.1%	40.2%
Solar	0.0%	0.1%	0.2%	0.7%	2.3%
Marine	0.0%	0.2%	0.5%	2.1%	4.0%
Biomass	0.0%	0.0%	0.0%	0.0%	0.0%
Hydro	1.5%	1.6%	1.5%	1.4%	1.3%
Coal CCS	0.0%	2.1%	3.1%	4.8%	6.2%
Gas CCS	0.0%	0.8%	3.3%	7.2%	10.3%
Imports	0.0%	0.0%	0.0%	0.0%	0.0%
Total:	**100%**	**100%**	**100%**	**100%**	**100%**

25.3 Technology mix for UK electricity supply for National Grid scenario.

National Grid	Percentage of Technology to Electricity Mix				
Year	**2010**	**2020**	**2030**	**2040**	**2050**
Electricity (GWh)	373,100	382,400	447,900	498,700	577,500
MtC limit	54.53	16.07	0.05	0.05	0.05
Nuclear	14.1%	10.7%	18.5%	26.8%	33.3%
Coal	36.9%	23.9%	2.5%	0.9%	0.0%
Natural Gas	42.9%	42.1%	32.4%	10.3%	0.0%
Oil	0.6%	0.0%	0.0%	0.0%	0.0%
Wind Onshore	3.0%	8.5%	9.0%	6.9%	5.5%
Wind Offshore	1.1%	10.3%	24.9%	29.1%	24.6%
Solar	0.0%	0.1%	0.2%	0.7%	2.1%
Marine	0.0%	0.1%	0.1%	0.5%	1.0%
Biomass	0.0%	0.0%	0.0%	0.0%	0.0%
Hydro	1.4%	1.5%	1.4%	1.3%	1.2%
Coal CCS	0.0%	2.1%	7.3%	15.6%	21.4%
Gas CCS	0.0%	0.8%	3.6%	7.9%	10.9%
Imports	0.0%	0.0%	0.0%	0.0%	0.0%
Total:	**100%**	**100%**	**100%**	**100%**	**100%**

25.4 Technology mix for UK electricity supply for Markal and Urban Two scenarios.

Markal	Percentage of Technology to Electricity Mix				
Year	**2010**	**2020**	**2030**	**2040**	**2050**
Electricity (GWh)	363,300	363,300	399,500	412,900	526,300
MtC limit	54.53	16.07	0.05	0.05	0.05
Nuclear	14.5%	11.9%	23.5%	37.0%	41.8%
Coal	36.7%	25.1%	2.8%	1.1%	0.0%
Natural Gas	42.7%	41.9%	34.8%	5.3%	0.0%
Oil	0.6%	0.0%	0.0%	0.0%	0.0%
Wind Onshore	3.0%	7.9%	7.8%	5.1%	3.0%
Wind Offshore	1.1%	8.3%	17.3%	18.5%	13.5%
Solar	0.0%	0.0%	0.0%	0.0%	0.0%
Marine	0.0%	0.4%	1.7%	6.9%	9.8%
Biomass	0.0%	0.0%	0.0%	0.0%	0.0%
Hydro	1.5%	1.6%	1.5%	1.5%	1.2%
Coal CCS	0.0%	2.2%	7.3%	16.4%	20.3%
Gas CCS	0.0%	0.8%	3.5%	8.3%	10.4%
Imports	0.0%	0.0%	0.0%	0.0%	0.0%
Total:	**100%**	**100%**	**100%**	**100%**	**100%**

25.5 Electricity production, supply mix and natural gas composition

Electricity

The UK electricity mix over the next 40 years is likely to change substantially (BWEA, 2010) however, the actual mixes in 2050 are hard to predict. According to some sources, a greener and more efficient electricity production and supply based on renewable decentralised systems is expected by then (BEG, 2006; DECC, 2009c; Harrison et al., 2010; HMGOV, 2011). Research suggests that by using predominately Carbon Capture and Storage (CCS) technologies for coal and gas electricity generation; GWP emissions could be reduced by (81% - 83%) compared with present day coal technology and by 59% for natural gas CCS over that without CCS (Holloway and Rowley, 2008; Odeh and Cockerill, 2008).

Targets set for 2030 and 2050 indicate a carbon intensity of 70 g CO_2/kWh and 30 g CO_2/kWh respectively (CCC, 2008) despite there being a possible increase in electricity demand (Gerber et al., 2010). It is worth noting, however, that current electricity mixes also exhibit differing carbon emission especially when comparing emissions during the day with those during the night when demand is lower but electric heating demand prominent. This change is recognised within the industry where baseline production, during the small hours, such as nuclear and natural gas are used, in preference to more the more polluting and costly electricity production from coal (Realtime, 2011).

Current electricity mixes are first studied based on the GB electricity mix (2010) (DECC, 2010a). Scenario production mixes up to 2050 are also studied including those that recognise the UK’s interim and final carbon emission reduction target levels over the 1990 levels (DECC, 2008; UKERC, 2009a) and provide emissions of approximately 50 g CO_2/kWh. Section 25.7 shows the electricity mix for 2010 initially used in this study.

Natural gas

Natural gas is supplied to householders through the national gas transmission and distribution system in the UK (NationalGrid, 2009a). The production and sourcing of UK natural gas has changed from being one of relative self-sufficiency in the peak year of 2000 - principally supplied from the North Sea, to one of net importer in recent years (DECC, 2013b). The composition of natural gas can present new difficulties with the importation of liquefied natural gas (LNG) (EC, 2011), however, the UK maintains important gas supply standards based on calorific value - usually between 37.5 MJ/m^3 to 43.0 MJ/m^3 (NationalGrid, 2013). A typical composition of natural gas is shown in section 25.8. Environmental GWP life cycle impacts from the use of natural gas in a typical condensing gas boiler are 237 g CO_2 eq./kWh whereas natural gas used in a combined cycle electricity plants impacts 394 g CO_2 eq./KWh (Papadopoulo et al., 2009).

The merits of natural gas decarbonisation and the development of a strategy remain at an early stage in the UK (Foreest, 2011; NationalGrid, 2009b). Its relatively clean characteristics and status as a default fossil fuel are likely to see the further supply of natural gas supplemented by renewable gas (NationalGrid, 2010) and natural gas power generation cleaning through carbon, capture and storage (Foreest, 2011).

25.6 Lifecycle environmental emissions from the combustion of natural gas.

Indicator	g per kWh
ADP elements	0.0001
ADP fossil	3,327
AP	0.227
EP	0.024
FAETP	1.894
GWP	262
HTP	8.3
MAETP	5,835
ODP	0.00004
POCP	0.061
TETP	0.231

25.7 Electricity production mix used within the electricity supply (DECC, 2010a) and approximate UK electricity mix 2010.

Technology	Contribution to electricity generation	Contribution to domestic heat and lighting
Nuclear	18.3%	
Coal (solid)	27.8%	2.5%
Natural gas Industrial gas Biogas Hydrogen	44.1% 0.6% 0.5% -	72%
Oil (liquid)	1.2%	2.5%
Wind – onshore Wind - offshore	2.5%	
Solar – PV Solar - thermal	- -	
Marine	-	
Biomass	-	
Hydropower Pumped storage	1.4% 1.0%	
Coal CCS	-	
Gas CCS	-	
Imports	-	
Waste incineration	0.6%	
Co-generation (wood)	2.0%	
Total:	100%	
% Contribution to domestic energy	**23%**	**77%**

25.8 Chemical composition of UK Natural Gas (BOC, 2011; Natgas, 2011).

Composition	Vol (%)
Methane -	88.88
Ethane -	5.57
Propane -	1.8
Carbon dioxide -	2.16
Nitrogen -	0.969
N-Butane -	0.301
Isobutane -	0.192
N-Pentane -	0.046
Isopentane -	0.048
N-Hexane -	0.0313
CV:	39.78 MJ/m^3
RD:	0.777
Wobbe Index:	49.95 MJ/Nm^3